Stream Channel Morphology: Major Fluvial Disturbances in Logged Watersheds on the Queen Charlotte Islands

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This study was undertaken as part of the Fish/Forestry Interaction Program (FFIP), a multidisciplinary research study initiated in 1981. The program was started following a series of major winter storms in 1978 that triggered landslides over much of the Queen Charlotte Islands forest land base. Originating on steep slopes, many slides deposited tonnes of debris in streams and on valley flats. The events raised private and public concerns over logging practices on the Islands and prompted the establishment of the 5-year program. Overall objectives of FFIP were:

- to study the extent and severity of mass wasting and to assess its impacts on fish habitat and forest sites.
- to investigate the feasibility of rehabilitating stream and forest sites damaged by landslides.
- to assess alternative silvicultural treatments for maintaining the improving slope stability.
- to investigate the feasibility and success of using alternative logging methods, including skylines and helicopters, and by logging planning to reduce logging-related failures.

The program is jointly funded by direct appropriations from the Canada Department of Fisheries and Oceans, the B.C. Ministry of Forests and Lands (Research Branch), and the B.C. Ministry of Environment and Parks (Fisheries Branch). Participating agencies include the Canadian Forestry Service (Pacific Forestry Centre), and the Forest Engineering Research Institute of Canada (FERIC), Vancouver, B.C.

Program results are published through the B.C. Ministry of Forests and Lands, Land Management Report series, as well as in papers presented at symposiums, conferences, and through technical journals.

For information about the program contact Ministry of Forests and Lands, Research Branch, 1450 Government Street, Victoria, B.C. V8W 3E7.

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ABSTRACT

Reconnaissance investigations of disturbed stream habitats early in the Fish/Forestry Interaction Program studies identified extensive, recently accumulated sediments in mid-reaches of some streams. Channel width has increased by up to 10 times, and the depositional zone is of order 1 km in length. From historical air photo and land use studies it was determined that the sediment wedges were initiated by streamside and in-stream logging practices before 1970.

A long term sediment budget was estimated for each basin to determine the relative importance of adjacent stream bank erosion (on-site land use effect) and other sediment sources -- including off-site land use effects -- in contributing to the sediment wedges. The most significant sediment sources in each basin were assessed in the field: minor sources were estimated from regional results. Stream banks and landslides were estimated to contribute two-thirds to three-quarters of all sediment delivered to the streams, with stream banks accounting for half or more of the sediment in three of four cases. Sediment comparisons between stream bank and bed sediments confirm the local provenance of the material.

Sediment stored in the wedges varies from all of the +1-mm input since disturbance, to possibly as little as one-quarter of the material. Long-term sediment outputs as bed load transport vary from 0 to about $10^3 m^3/yr$. Because far more sediment is stored in the channels than is annually transported out, the wedges will persist for a long time.

ACKNOWLEDGEMENTS

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1 INTRODUCTION

1.1 Context

The coastal watersheds of the Pacific Northwest superimpose two of the most economically important renewable resource industries in the region: forestry and fisheries. For the economic well-being of British Columbia, it is essential that the future management of these coastal watersheds benefits both industries. It is well established that timber harvesting and road construction can accelerate soil erosion on hillslopes and sedimentation in streams, with consequent alteration of fish habitat. Therefore, understanding the movement of sediment in a watershed is a prerequisite to successful multiple resource management. Appraisal of sediment erosion, transport, and deposition processes must precede the design of effective erosion control measures (Swanson and Fredriksen 1982).

To quantify the movement of sediment in small drainage basins, a sediment budget is constructed. The basic form is:

$$I + \Delta S = \emptyset$$

where I = sediment input

ΔS = change in sediment storage

$\emptyset$ = sediment output

Swanson *et al.* (1982b) recently presented a compilation of sediment budget and routing studies conducted in forested watersheds in the Pacific Northwest. These investigations assess the relative importance of sediment sources and changes in storage within a basin, and the relations among the various material transfer processes.

The role of these processes is confounded by their spatial and temporal variability (Swanson *et al.* 1982a) and the possibility that individually small effects may have a pronounced downstream cumulative impact (Rice 1981; Salo and Cederholm 1981). In addition, the erosional response to a climatic event is governed by the intensity and duration of the event, and by its timing with respect to the antecedent history. This may be especially true in steep, geomorphically active forested terrain,

where the recovery rate of the system may be long relative to the frequency of climatic events that trigger geomorphic response (Kelsey 1982). The effect of these complicating factors makes it imprudent to extrapolate results and, hence, management prescriptions between non-adjacent watersheds. More case studies are needed to rectify this situation, particularly in British Columbia (Pearse 1982) where, until recently, the only major project undertaken was at Carnation Creek (Hartman 1982).

The Fish/Forestry Interaction Program (FFIP) was initiated in 1979 to resolve management uncertainties in areas of intensive mass wastage in the Queen Charlotte Islands (Poulin 1984). This study represents one component of the project and investigates stream channels in which major deposition of fluvial sediments was observed.

1.2 Objectives

The general approach of FFIP was to compare many logged basins with forested basins, selected on the basis of similar physical conditions. This "extensive post-treatment" design (Hall et al. 1978) provides a wide spatial and temporal perspective from short-term synoptic investigations.

During an early reconnaissance, it became apparent that some of the logged watersheds had recent, unusually large accumulations of sediment in their stream channels (E. Harding, pers. comm., 1981). These "sediment wedges", as they are called in this report, occur in the stream mid-reaches, have a zone of deposition whose width is an order of magnitude greater than the width of the stream channel itself, can be kilometres long, and have neither a scoured upstream channel nor, necessarily, a major log jam at the downstream terminus. In contrast, widespread debris flow/debris torrent deposits occur in the basin headwaters and have, immediately upstream of the depositional zone, a length of scoured channel that is hundreds of metres long. The deposits are usually delimited at their downstream terminus by a major log jam. These differences between mass wastage deposits and sediment wedges

reflect fluvial reworking of sediment that entered the stream mid-reaches in abundant volume.

To investigate the origin and effects of these fluvial phenomena, the study addressed four main questions:

i. What were the sources of the sediment?
ii. What caused its appearance in the stream channels?
iii. How mobile is the sediment?
iv. What are the impacts of the sediment wedges on the stream channel morphology?

In meeting these objectives, reconnaissance surveys were conducted in several unlogged and logged basins, followed by the detailed study of four logged basins that exhibited well-developed sediment wedges. Sediment budgets were estimated for these channel-zone wedges. This detailed examination of sediment transfer processes represents a departure from the synoptic and statistical approach that was generally taken in FFIP.

1.3 Study Watersheds

1.3.1 Environment

The four study watershed channels lie within the Queen Charlotte Ranges physiographic region (Figure 1). Mountain Creek and Lagins Creek tributary share the same headwater divide on Graham Island; the former discharges into Rennell Sound to the north, while the latter flows into the main stem of Lagins Creek and thence into Long Inlet to the southeast. On Moresby Island, Mosquito Creek tributary flows northward from Mount Moresby to its confluence with the main stem of Mosquito Creek; Armentières Creek empties into Chaat Narrows. The geology of the Queen Charlotte Islands is detailed by Sutherland Brown (1968) and reviewed by Beaven (1986). The predominant rock types in the four study basins are shown in Table 1. The rocks are usually well bedded, jointed, or fissured, thereby promoting the

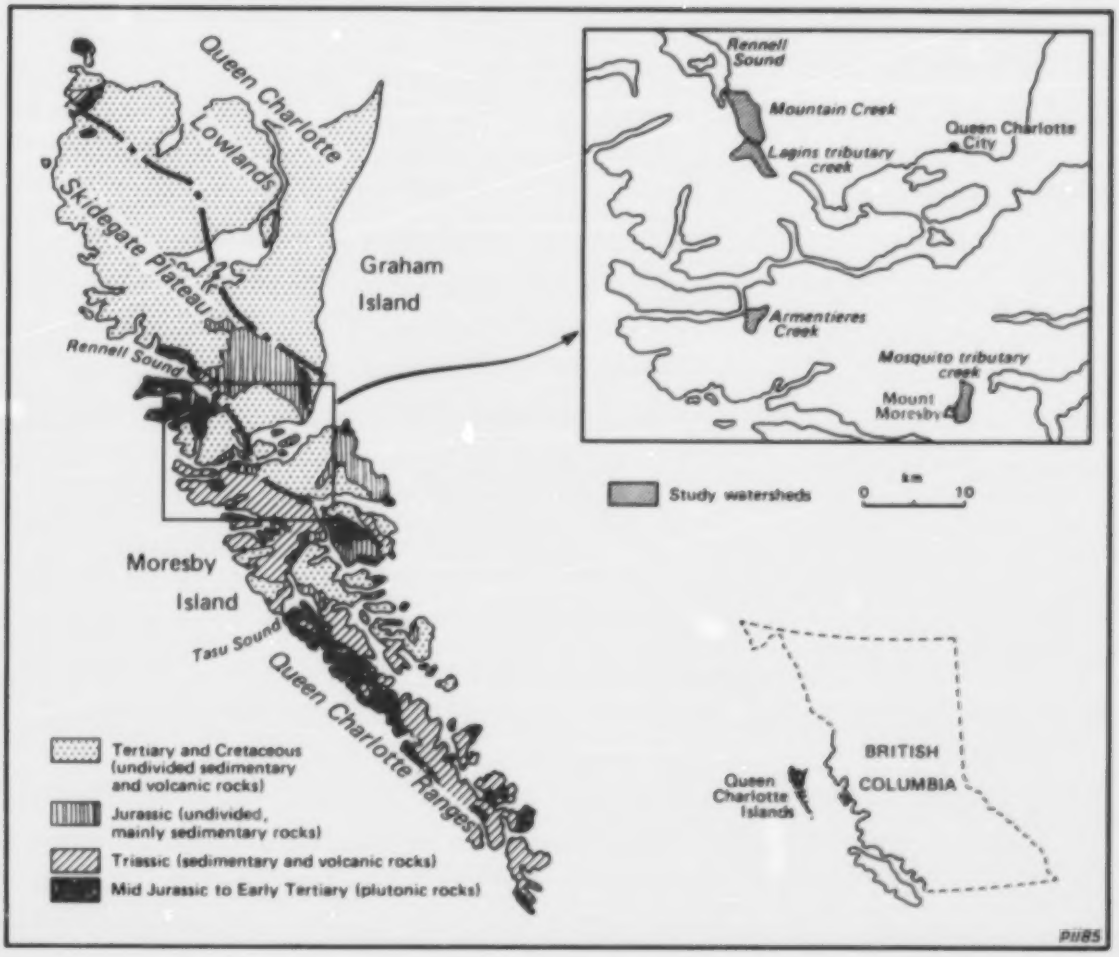


FIGURE 1. Location map of study basins, including generalized geology and physiography of the Queen Charlotte Islands.

TABLE 1. Physiography and logging history of the study watersheds

Characteristic	Watershed: Armentières	Mosquito trib.	Lagins trib.	Mountain
Physiography, geology:				
Drainage area[a] (km^2)	3.93	5.38	5.92	12.64
Drainage length[b] (km)	2.75	5.05	5.60	7.30
Drainage relief[c] (m)	490	860	770	910
Average gradient[d]	0.18	0.17	0.14	0.12
Drainage density (km/km^2)[e]	4.2	6.1	5.9	6.7
Highest stream order[e]	4	4	4	5
Major rock type	Basalt flows, pillow lavas, pillow breccia and tuff, minor limestone, volcanic sandstone and salal		Dark grey calcareous siltstone, greywacke conglomerate and minor volcanic rocks	Quartz monzonite granite, granodiorite, and quartz diorite
Logging history:				
Dates logged	1962-65 1967-69	1963-69	1970-77	1958 1965-67
Area logged (km^2)[e] (% basin)	0.29 (7.4) 0.46 (11.7) 0.75 (19.1)	1.08 (20.1)	0.63 (10.6)	0.06 (0.5) 1.18 (9.3) 1.24 (9.8)
Maximum road length (km)	1.20	5.01	5.50	6.73
Road density (km/km^2)	0.31	0.93	0.93	0.53
Road width (m)	5.0	9.4	11.2	7.5

TABLE 1. (Continued)

Characteristic	Watershed			
	Armentières	Mosquito trib.	Lagins trib.	Mountain
Logging activities:[f]				
Logging method	Hand (to 1965) Skidded	High lead	Skidded (to 1974) High lead	Skidded (1958) High lead
Logging to stream bank	extensive	extensive	extensive	extensive
Cross-stream felling	extensive	limited	limited	extensive
Cross-stream yarding	extensive	extensive	extensive	extensive
In-stream skidding	extensive	none	limited	limited
Stream avulsion along road	extensive	limited	extensive	limited
Road bridge collapse	none	major	minor	none

[a] Drainage area: area enclosed by the watershed boundary, from 1:50 000 scale maps.
[b] Drainage length: length of the main channel from its outlet to the basin divide, from maps.
[c] Drainage relief: height difference between the main channel at its outlet and the highest point at the basin divide, from maps.
[d] Average gradient: ration of drainage relief to drainage length.
[e] From 1:10 000 air photography; highest stream order after Strahler (1952).
[f] From field observations and interviews with logging contractors and supervisors.

penetration of water, and associated weathering, to great depths (Sutherland Brown 1968; Alley and Thomson 1978). As a result, the bedrock is highly susceptible to erosion. Movements on the Queen Charlotte Fault are responsible for the highest incidence of seismic activity in Canada (Sutherland Brown 1968). Between 1899 and 1974 there were 1268 earthquakes, the largest being a Richter magnitude 8.0 event in 1949 with the epicenter located just off Graham Island (Milne et al. 1978). Alley and Thomson (1978) assert that on tenuously stable hillslopes the shaking stress of earthquakes triggers widespread mass-wasting. The wet soil moisture conditions preceding the 1949 earthquake probably aggravated the occurrence of slope failures (E.J. Karanka, pers. comm., 1984).

Field investigations of surficial deposits by the author were restricted to examinations of stream bank materials. In the four study watersheds, the banks consist primarily of fluvial deposits, occasionally underlain by till or bedrock and overlain by colluvium; the material usually is poorly sorted and stratified, with moderately-well imbricated sub-angular to sub-rounded gravels of varied lithologies, in a loose or weakly cemented fine to coarse sand matrix. Organic deposits are associated mainly with backwater and overbank accumulations of sandy and finer sediments, which may also contain paleosols (buried soils). Till is more compact and finer textured than fluvial deposits, even after weathering, and limited exposures are found along Mountain Creek and Mosquito Creek tributary. Colluvium can be derived from bedrock or till, though more frequently the former, and is coarser textured than fluvial deposits, with angular to sub-angular gravels and cobbles in a sandy matrix. The lithology and texture of all surficial material are strongly influenced by the parent material from which it was derived and, consequently, are highly variable.

The materials mantling the slopes in the study watersheds are not known, except for Mosquito Creek tributary which was mapped in

1979 by Dr. T. Lewis (MacMillan Bloedel). There, steep bedrock slopes are covered by a colluvial veneer, except near the confluence with Mosquito Creek where the footslopes are masked by a morainal blanket.

In the Rennell Sound region, intense weathering and mass-wasting processes have produced abundant colluvium, which testifies to the inherent instability of the terrain (Alley and Thomson 1978; Wilford and Schwab 1982). This situation occurs throughout the Queen Charlotte Ranges, where there are recurrent slope failures in the tenuously stable and non-cohesive morainal and colluvial materials, and in bedrock.

The influence of bedrock geology and glacial history is expressed topographically by the steep valley slopes in the four study watersheds. Typically, the slopes are concave or straight, with gradients ranging from 0.5 (25°) on the footslopes to more than 1.7 (60°) in the headwaters, and averaging between 0.7 (35°) and 0.9 (40°) on the mid-slopes. However, the width of the valley bottoms varies considerably. About half of the Lagins Creek tributary catchment is low-gradient terrain, so slope transfer of sediment reaches the creek only in the headwaters. By contrast, Armentières Creek, Mountain Creek, and Mosquito Creek tributary are bordered by a narrow floodplain zone and restricted footslope area, which allows material to be transferred from the steep valley walls directly into the creek. In general, the zone of relatively flat terrain that separates the slopes from the streams increases in width downstream.

As a result of the instability, soils are disturbed and their development hindered by weathering and erosion processes and by the windthrow of large trees (Valentine et al. 1978). In the Queen Charlotte Ranges, which have abundant rainfall, little snowfall, and mild winter temperatures, the soils have a high moisture content for most of the year, resulting in predominantly Ferro-Humic Podzol soils

(Valentine et al. 1978). However, the nature of the surficial deposit has an important influence on the character of the overlying soil: the soils developed on colluvium are usually deeper and better drained than those on morainal and gravelly fluvial materials. Cemented horizons occur on the latter, where there is a net accumulation of organic matter and development of Folisols (Valentine et al. 1978).

The climate of the Queen Charlotte Islands is perhumid, with cool summers and mild winters. Annual rainfall varies from 1500 mm on the eastern plains to more than 5000 mm on some west coast slopes (Alley and Thomson 1978) where storms, known to have initiated mass-wasting, annually exceed 130 mm in 24 hours (Wilford and Schwab 1982). Snow is ephemeral at sea level and is confined mainly to elevations above 600 m. As in much of the Pacific Northwest, there is an uneven distribution of annual precipitation, with approximately 80% occurring from October through March. Destructive winds occur more frequently in the Queen Charlotte Islands than elsewhere in Canada, with recorded gusts approaching 200 km/hr (Alley and Thomson 1978).

The four study watersheds lie within the Coastal Western Hemlock biogeoclimatic zone, which is the wettest and most productive forest zone in British Columbia (Valentine et al. 1978). Sitka spruce (Picea sitchensis), western hemlock (Tsuga heterophylla), and western redcedar (Thuja plicata) are the main forest types, with mountain hemlock (Tsuga mertensiana) and Alaska yellow-cedar (Chamaecyparis nootkatensis) present to a lesser extent. The dominant deciduous species is red alder (Alnus rubra), which rapidly colonizes disturbed sites such as stream banks, mass movement tracks, and abandoned logging roads. Although this results in the short-term loss of productive coniferous forest sites, the rapid regeneration of a vegetative root system aids in stabilizing residual soils in areas of intensive mass wasting. This is especially critical as the cover of shrubs and herbs is less than 20% (Smith 1982) and rooting depths are

usually less than 30-40 cm (Wilford and Schwab 1982). At present, the logged stream banks and valley flats in the study watersheds support a dense cover of red alder interspersed with young conifers and an understorey of shrubs and herbs, while the logged slopes are revegetated primarily by shrubs, herbs, bryophytes, and young conifers.

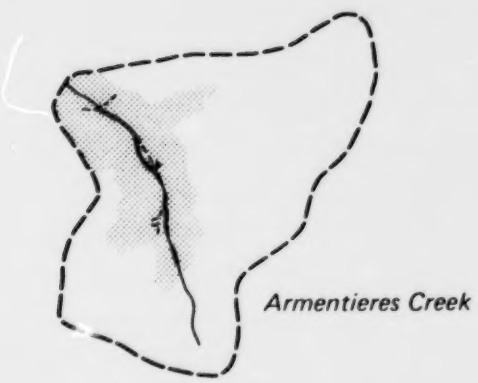
1.3.2 Land management

The size, location, and date of clearcut areas and roads in the study watersheds, obtained from air photo analyses, are shown in Table 1 and Figure 2. The following sections describe the logging history of each basin, drawing on conversations with those individuals directly involved and, whenever possible, independently confirmed by field investigations and/or air photo analyses.

Armentières Creek (Figure 2A)

The Armentières Creek basin was logged by Goodwin Johnson Ltd. in 1962-1963, Bernie Ralph in 1964-1965, Paul Egger in 1967-1968, and finally by Goodwin Johnson Ltd. in 1969 (Goodwin Johnson, pers. comm., 1983; Werner Funk, pers. comm., 1983). The only information available about the early years of logging, near the mouth of the basin, is that skidding was conducted along trails rather than in the creek (W. Funk, pers. comm., 1983; confirmed by air photo analysis), and that cross-stream felling was avoided (G. Johnson, pers. comm., 1983). More is known about the logging of the upper watershed between 1967 and 1969. The area was tractor skidded using skid trails (G. Johnson, pers. comm., 1983; W. Funk, pers. comm., 1983; confirmed from field investigations and air photo analyses), except where the stream channel was ill-defined as the result of its naturally multi-branched condition (G. Johnson, pers. comm., 1983; confirmed by air photo analysis) and/or was redirected along skid trails during the spring freshets (G. Johnson, pers. comm., 1983).

A. Armentières Creek



B. Mosquito Creek tributary

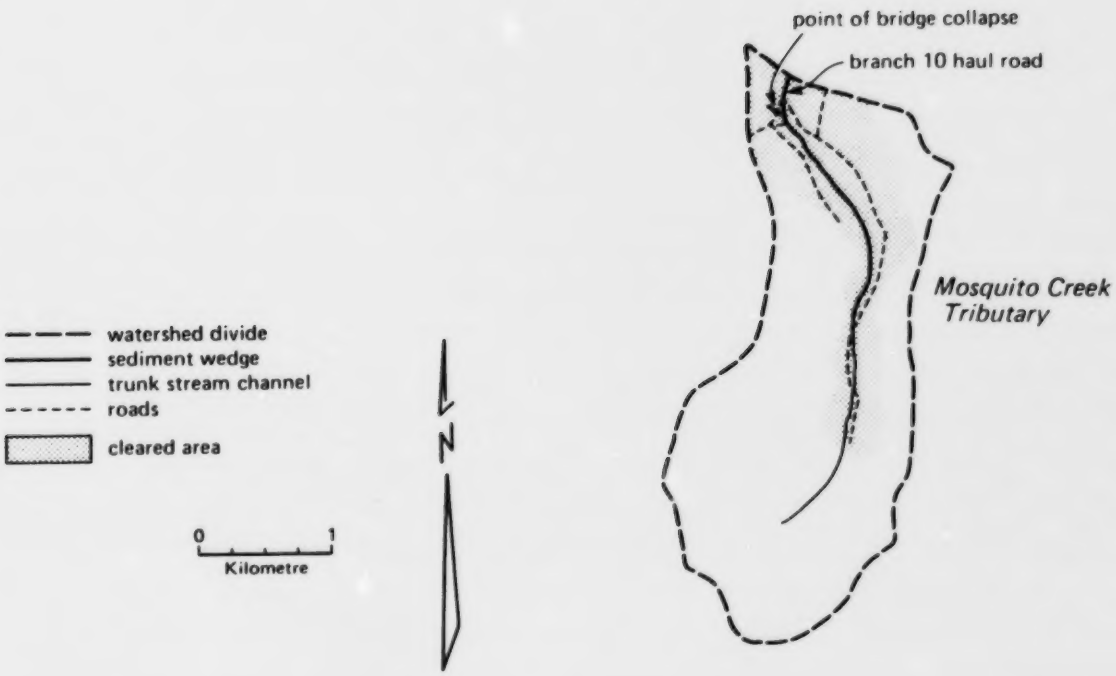
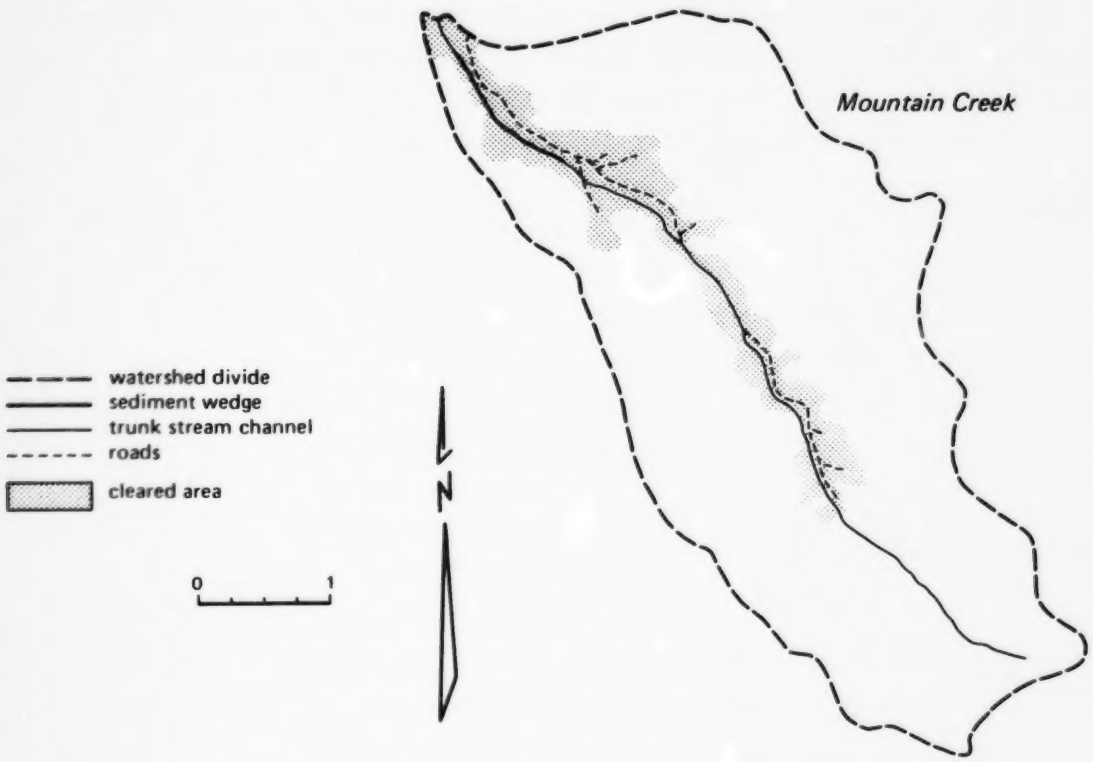


FIGURE 2. Logging activities in the study watersheds.

C. Mountain Creek



D. Lagins Creek tributary

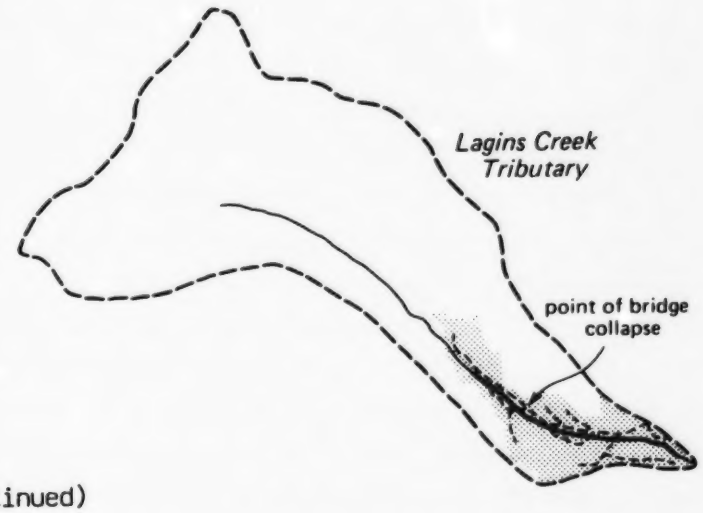


FIGURE 2. (Continued)

Mosquito Creek Tributary (Figure 2B)

This watershed was clearcut logged by Rayonier (now Western Forest Products) beginning in 1963, using high-lead yarding and haul roads (Hank Hanson, pers. comm., 1983). As seen in Figure 2B, the upper two-thirds of the basin contains a single haul road along one side of the creek, necessitating the cross-stream yarding of timber from the opposite slopes. Cross-stream felling was avoided whenever possible (H. Hanson, pers. comm., 1983) and thus the large amount of in-stream timber visible in the 1964 air photos may be attributable to yarding rather than felling practices.

Also significant are the bridge construction activities in the basin: the most downstream bridge was built in 1962 using approximately 1500 m^3 of gravel, and collapsed following logging, partly because of its sub-standard construction (H. Hanson, pers. comm., 1983). As a result of the large input of gravel, the creek bed aggraded downstream (see Section 3.2) and the flow was diverted along Branch 10 haul road. Additional sediment probably was supplied to the creek at the former bridge crossing by the surface erosion of convergent haul roads (H. Hanson, pers. comm., 1983). If the three other bridge crossings were constructed similarly, their subsequent collapse would have introduced into the creek a considerable volume of gravel, which may have contributed to the large, fluvial sediment accumulation downstream. The construction cannot be confirmed, but the bridges have gone.

Mountain Creek (Figure 2C)

The Mountain Creek watershed tree farm licence was owned by British Columbia Forest Products (now part of CIPA Industries) and it was clearcut logged in two stages. Beginning in 1958, timber was skidded along the multi-branched lower reaches of the creek, until the provincial Fish and Wildlife Branch enforced the use of high-lead yarding and haul roads between 1965 and 1967 (V. Wellburn, pers. comm., 1983; confirmed by air photo analysis). From the 1966 air

photos, cross-stream felling is evident; the only haul road lies on the east side of the creek, so timber from the opposite slopes was yarded across the stream. In the lower reaches, a branch road crosses the creek, but neither field investigations nor air photo analyses indicated the construction of a bridge. In the upper reaches, the haul road was constructed close to the stream, so that, at present, the creek flows preferentially along a section of the road.

Lagins Creek tributary (Figure 2D)

This basin was logged by Robert Leblanc on contract to Goodwin Johnson Ltd., between 1970 and 1977 (Goodwin Johnson, pers. comm., 1983). From the start of operations until the end of 1974, the steep slopes were high-lead yarded, while the flatter ground was clearcut by high-lead and skidder methods (Dick McDiarmid, pers. comm., 1983; G. Johnson, pers. comm., 1983). Timber was hauled to the beach by a cat and arch skid on the east side of the creek (D. McDiarmid, pers. comm., 1983) and along the creek in its multi-branched upper reaches (G. Johnson, pers. comm., 1983). In 1975, the Fish and Wildlife Branch prohibited cross-stream felling and in-stream skidding, so skid trails were used in the upper reaches (G. Johnson, pers. comm., 1983) and haul roads were built elsewhere (G. Johnson, pers. comm., 1983; D. McDiarmid, pers. comm., 1983). The latter were never elevated properly nor were culverts installed, and in some areas the road was lower than the surrounding ground (D. McDiarmid, pers. comm., 1983). As a result, when the main bridge collapsed during a 1976 winter storm, Lagins Creek tributary and many of the smaller ones, began flowing down the haul road (G. Johnson, pers. comm., 1983; D. McDiarmid, pers. comm., 1983) which, as field investigations show, has become the contemporary stream channel. Truck hauling was completed along an upgraded haul road on the west side of the creek

without further major stream disturbance (D. McDiarmid, pers. comm., 1983). In conclusion, ground yarding and poor road construction significantly influenced the preferred hydrologic pathways within this watershed.

2 METHODOLOGY

The overall rationale of this study is shown diagramatically in Figure 3, and the individual components of this framework are discussed in the following sections.

As a preliminary exercise, rates of sediment production (the amount of sediment mobilized by a process on hillslopes) and sediment delivery (the amount that reaches a stream channel), by various transfer processes, were collated from published results of other studies in the Pacific Northwest. A detailed literature review is given in Roberts (1984) and the summary results are presented in Table 2. Because site-specific factors cause sediment transfer rates to vary greatly within the Pacific Northwest, a range of rates is given for each process. (Furthermore, the ranges for forested and logged sites sometimes are based upon data from different studies in different places and may not be comparable.) The most important processes are landslides and stream banks (riparian) erosion. "Landslide" is used here as a collective term for debris slide, debris avalanche, flow, and torrent. Road surface erosion and soil creep on logged terrain also have high delivery rates (Table 2), but these were derived from basins that were more extensively clearcut, included steeper slopes, and had greater road densities than in the study basins. Therefore, sediment delivery by riparian and landslide erosion was measured directly from air photos, while the representative process rates of Table 2 were used to estimate sediment delivery by the distributed processes of soil creep, tree throw, and surface erosion.

2.1 Air Photo Analyses: Sediment Production and Delivery

The federal, provincial, and private photography used in this study provides a temporal coverage of 50 years, at scales ranging between 1:10 000 and 1:63 360 (see Table 3).

2.1.1 Hillslope erosion

Photogrammetric maps and measurements of mass movement events in the four study watersheds were made with the Wild A6 stereo-plotter

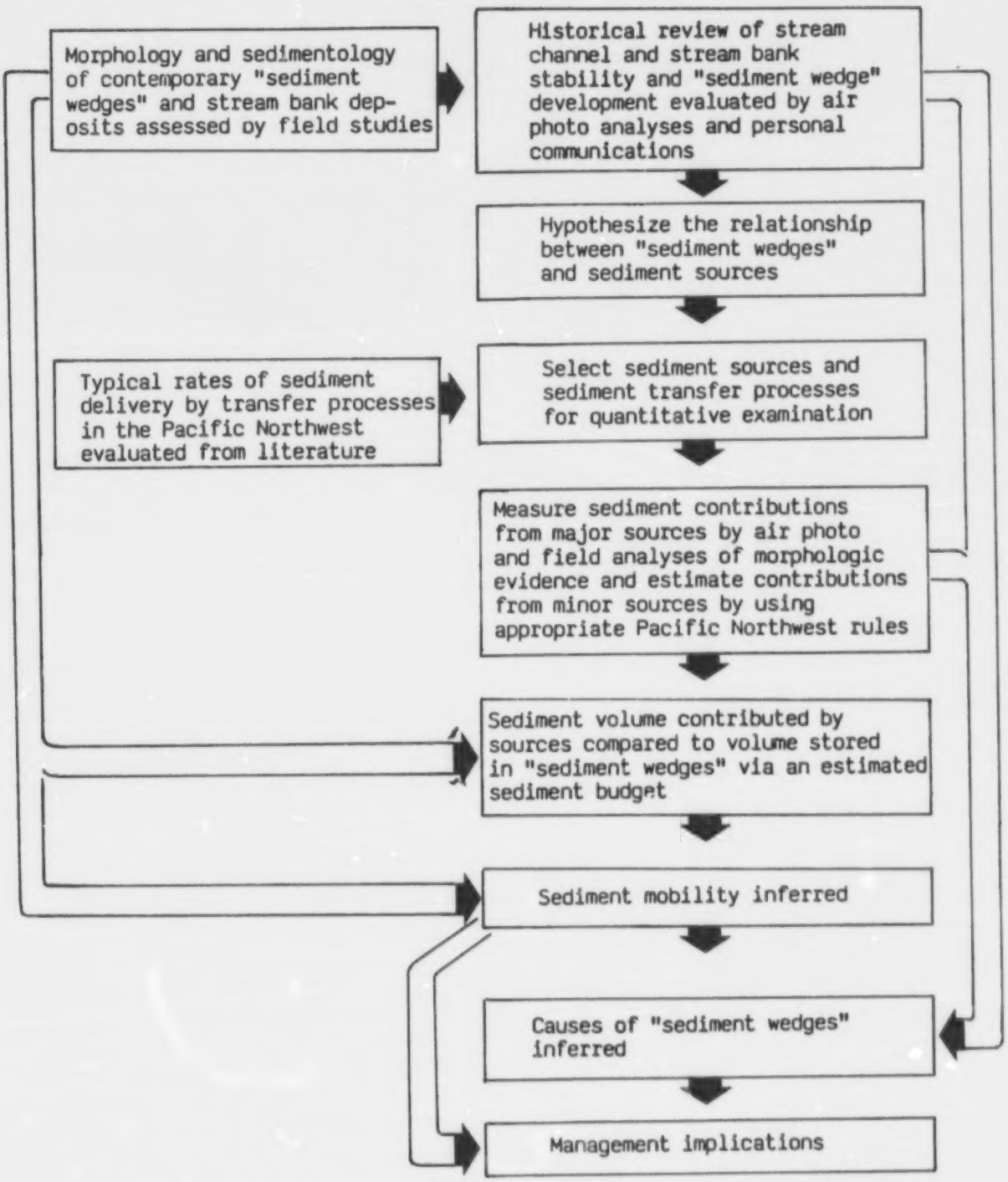

Morphology and sedimentology of contemporary "sediment wedges" and stream bank deposits assessed by field studies
Historical review of stream channel and stream bank stability and "sediment wedge" development evaluated by air photo analyses and personal communications
Hypothesize the relationship between "sediment wedges" and sediment sources
Typical rates of sediment delivery by transfer processes in the Pacific Northwest evaluated from literature
Select sediment sources and sediment transfer processes for quantitative examination
Measure sediment contributions from major sources by air photo and field analyses of morphologic evidence and estimate contributions from minor sources by using appropriate Pacific Northwest rules
Sediment volume contributed by sources compared to volume stored in "sediment wedges" via an estimated sediment budget
Sediment mobility inferred
Causes of "sediment wedges" inferred
Management implications

FIGURE 3. Flow diagram of study design.

TABLE 2. Representative rates of sediment production on slopes and delivery to streams in the Pacific Northwest

Process	Watershed condition	Rate of sediment production	Rate of sediment delivery to stream	Sources
			[m^3/(km channel·yr)]	
Soil creep	Forested slopes	1 - 3 mm/yr	0.9 - 4	Dietrich & Dunne (1978) Lehre (1982) Swanson et al. (1982a) Madej (1982)
	Logged slopes	2 - 5 mm/yr	6 - 40	Barr & Swanston (1970) Swanston (1981)
Tree throw	Forested slopes	1 - 2 mm/yr	0.1 - 1	Madej (1982) Reid (1981) Swanson et al. (1982a) Dietrich et al. (1982)
Landslides[a]	Forested	9 - 72 m^3/(km^2 basin·yr)	3 - 10	O'Loughlin (1972) Fiksdal (1974) Morrison (1975) Swanson & Dyrness (1975) Reid (1981) Swanson et al. (1981) Lehre (1982) Madej (1982) Swanson et al. (1982a)
	Logged; built roads	22 - 3,500 m^3/(km^2 basin·yr)	9 - 20[b]	O'Loughlin (1972) Swanson & Dryness (1975) Reid (1981) Swanson et al. (1981) Madej (1982)
Surface erosion	Forested slopes	4 - 10 m^3/(km^2 basin·yr)	0.4 - 0.9	Lehre (1982) Swanson et al. (1982a) Megahan & Kidd (1972b)

TABLE 2. (Continued)

Process	Watershed condition	Rate of sediment production	Rate of sediment delivery to stream (m^3/[km channel·yr])	Sources
	Slide scars	1000 - 4000 $m^3/(km^2$ scar·yr)	0.09 - 5	Reid (1981) Lehre (1982)
	Logged slopes	16 $m^3/$ (km^2 basin·yr)	Not available[c]	Megahan & Kidd (1972b)
Roads	During use	10 000 - 15 000 $m^3/(km^2$ road·yr)		Reid (1981) Reid & Dunne (1984) Lehre (1982)
	First year of disuse	1000 - 2000 $m^3/(km^2$ road·yr)	5 - 30	Megahan & Kidd (1972a) Hornbeck & Reinhart (1964)
	Abandoned	100 - 500 $m^3/(km^2$ road·yr)		
Stream banks[d]	Forested	2 - 11 $m^3/$(km channel·yr)	2 - 11	Reid (1981) Lehre (1982)
	Logged	160 - 420 $m^3/$(km channel·yr)	160 - 420	Toews & Moore (1982)

[a] This term includes debris slides, avalanches, flows, and torrents.
[b] Derived from Reid (1981) and Madej (1982). Higher rates of sediment production reported in other studies cannot be expressed in $m^3/$(km channel·yr) because drainage densities are not cited.
[c] Rate cannot be expressed in $m^3/$(km channel·yr) because drainage density is not cited.
[d] Higher delivery rates under forested conditions (up to 160 $m^3/$(km channel·yr)) are reported by Toews and Moore (1982). As with their post-logging rates, this reflects averaging over short study reaches rather than along the entire drainage network.

TABLE 3. Available air photography

Photography			Creek covered			
Date	Approx. scale	Source	Armentières	Mosquito	Mountain	Lagins
1933	1:31 680	Federal	x		x	
1937-38	1:31 680	Provincial		x		x
1954-55	1:63 360	Federal	x	x	x	x
1964	1:15 840	Provincial	x	x		
1966	1:15 840	Provincial			x	x
1974	1:63 360	Provincial	x	x	x	x
1976	1:15 840	Provincial	x	x	x	x
1979	1:63 360	Federal	x	x	x	x
1982	1:10 000	Private	x	x	x	

at the University of British Columbia, using the methods and standards outlined by Rood (1984). For purposes of analysis, each mass movement was subdivided into three zones: the initiation zone where most soil erosion occurs; the run-out (or depositional) zone where most debris is deposited; and the intervening transport zone, through which upslope material passes and additional soil erosion may occur.

The photogrammetric measurements of mass movements in the Mountain Creek, Mosquito Creek tributary, and Armentières Creek basins were made from the 1982, 1:10 000 scale air photos. Lagins Creek tributary watershed was analyzed using the 1976, 1:15 840 scale air photos. By identifying mass movements on the earlier sets of photography, and then relocating them on the most recent set, events of different age were mapped at a single 1:5 000 scale. Based on photo resolution, only those landslide scars with a surface area greater than 200 m^2 were measured and mapped; the number of smaller slides was noted. This procedure is consistent with that used by Rood (1984).

The length and width of slide scars were measured from 1:5000 scale maps to within ±0.5 m on the ground. Similar precision was obtained from the vertical scale on the Wild A6, but because the depth of most slides is less than 1 m (Smith 1982), height information was used primarily for slope gradient calculations. The depth to bedrock in the initiation zone was taken as 0.50 m ± 0.06 m from field measurements (R.B. Smith, pers. comm., 1984), and the depth of soil eroded from the transport zone was assumed to be 0.25 m (Rood 1984). The product of these dimensions, which gives the volume of eroded sediment, was compared to the independently calculated volume of deposited sediment to corroborate the assumptions.

2.1.2 Riparian erosion

The erosion of stream banks in the four study watersheds was measured directly from air photos that were uncorrected for tip or tilt displacements. The extra time involved in photogrammetric mapping was not justified because the absolute displacements are usually small, and the relative displacement of a stream channel is much less than that of a hillslope. The procedure used in each watershed was as follows:

i. Along the main stem of each creek, the edges of the stream banks were traced from the earliest available set of photos (1933 or 1937-38), the set flown immediately before or during logging (1964 or 1966), the set flown after the completion of logging (1976), and the most recent set of photos (1982).

ii. As these tracings were at different scales, they were redrawn to a common scale (usually the largest) by means of a Saltzman projector.

iii. The width of the stream channel was then measured perpendicular to the stream banks, at 50-m intervals, to within ±0.8 m on the ground. Where a stream channel was divided around an island, the width of each branch was measured and the two widths

totalled to produce a single value. The first cross-section was located at the same place in each set of air photos, and always downstream of the sediment wedge; channel widths were measured as far upstream as air photo resolution permitted (usually up to second-order channels).

iv. Temporal changes in channel width prior to logging (from 1930's and 1960's air photos), before and after logging (from 1960's and 1976 air photos), and since the completion of logging (from 1976 and 1982 air photos) were used to calculate areas of riparian land eroded.

Locating the edge of the stream banks was a major problem in areas with a dense forest canopy and in old, poor resolution air photography. In such situations, the crowns of trees assumed to be on or near the bank edge were used to delineate the margins of the stream channel.

Qualitative observations were made of changes in stream channel location caused by braiding or river diversion along a logging road, and these were ground checked during subsequent field investigations.

2.1.3 Road network

The length and width of logging roads in the four study watersheds were measured directly from air photos that were uncorrected for tip or tilt displacements. Average road width was measured from air photos taken during or shortly after logging, when the road right-of-way was most visible; total road length was measured from air photos taken after the completion of logging, when the road density was greatest. The results are summarized in Table 1.

The impact on stream channel morphology of bridge collapse and river piracy by logging roads was assessed qualitatively by air photo analyses and subsequent field investigations.

2.2 Field Measurements: Channel Morphology and Sediments

The following field investigations were carried out during the summer low flow period from June through August 1982, and during May 1983.

2.2.1 Channel morphology

To determine the length of a sediment wedge, the long profile was surveyed with a level, stadia, and chain. On average, successive stadia rod positions were 30 m apart, representing a compromise between time constraints and the delineation of a sediment wedge profile in sufficient detail.

The principal morphological features of a sediment wedge were mapped by standard surveying techniques, using a plane table, telescopic alidade, stadia rod, metric tape, and chain. A section of each sediment wedge, 500 m or more in length, was mapped at a scale of 1:500, using bench marks established during the long profile traverses.

Stream bank stability was assessed from measurements of bank undercut and overhang, and from examination of the material along exposed bank sections, at 50-m intervals. These rapid surveys were conducted along the main stem of each creek from their outlets up to their unlogged headwaters, enabling the relative importance of fluvial and non-fluvial sources of sediment to be evaluated qualitatively at the watershed scale.

Qualitative assessment of exposed stream bank sections was in terms of the size (texture), sorting, compaction, and stratigraphy of the material, and the shape, lithology, and imbrication of large clasts. From this information, the genetic origin and potential erodibility were inferred. Additional observations were made of paleosols and organic material, which were most apparent in banks composed of fine sediments. These lines of evidence provide a temporal framework within which the historical importance of episodic mass movements can be evaluated compared to continuous fluvial processes within the riparian zone.

2.2.2 Wedge sediments

To describe downstream trends, wedge surface sediments were sampled at both ends of a wedge and at two or three approximately equally spaced sites in between. At each site, a 30-m survey tape was stretched out parallel to the direction of flow, and the clast exactly beneath each half-metre mark was picked up (Wolman 1954). The a, b, and c axes of 50-60 clasts with a b-axis greater than 8 mm were then measured (8 mm is the minimum size of material that can be removed practically by hand). In addition, at each site a qualitative assessment was made of the angularity, lithology, and imbrication of large clasts.

Subsurface sediment was sampled at four or five sites along each wedge, coinciding with surface transect sites (in Lagins Creek tributary only surface sediment was sampled). The surface grains were removed and between 80 and 100 kg was recovered for field sieving.

The material was sieved into half phi classes between 64 mm and 8 mm, and weighed in the field according to a procedure similar to that described by Bray (1972). The material finer than 8 mm was weighed, quartered, and sealed in a sample bag for subsequent laboratory analysis. To simplify subsequent calculations, it was assumed that all the soil moisture was contained in the sub-8 mm fraction, because of the higher specific surface area and the small pore spaces in aggregate clusters of fines. Bray (1972) made the same assumption.

At two or three subsurface sample sites, the adjacent stream bank material was also sampled, using the same field and laboratory procedure for bulk sieve analysis. Stream banks may contain deposits of varying genetic origin. Where feasible, these materials were sampled in proportion to their exposed surface area.

3 RESULTS

The sources and mobility of the sediment wedges are evaluated in terms of a sediment budget (Section 3.1), while the causes are addressed in Section 3.2.

3.1 Sediment Budget

3.1.1 Sediment sources

In the following discussion, five sediment sources, each representing a group of erosion processes, are considered: slow mass movements, rapid mass movements (landslides in the broad sense), hillslope surfaces, road surfaces, and stream banks. The justification of those processes examined directly (landslides and stream bank erosion) and those assessed from representative process rates (soil creep, tree throw, surface erosion) was made in Section 2. The sources pertinent to this study are those that deposit their sediment into, or near to, the drainage network that is adjacent to, and upstream of, a sediment wedge.

The delivery of sediment from various sources within each watershed is summarized in Table 4. Contributions to the three sediment wedges in Armentières Creek are shown in Table 5 for periods before and after logging, covering the total standard period 1933-1982. A range of delivery volumes is presented for each sediment source: landslide and stream bank ranges incorporate the error associated with measurement imprecision, while the other source estimates reflect the range of representative process rates (indicated in Table 2). The total volume of sediment delivered to the contributing drainage network of each sediment wedge is presented as an extreme range -- the sum of all positive and negative extremes -- and as the most probable range (because all extremes are unlikely to arise together). The latter is the square root of the sum of squared errors, in which a non-statistical error (quoted as an outside limit, such as a measurement uncertainty) is assumed to be

TABLE 4. Volumes of sediment delivered to the streams from various sources[a]

A. Prior to logging[b]

Sediment source[c]	Armentières Cr. $\times 10^3 m^3$	%	Mosquito Cr. trib. $\times 10^3 m^3$	%	Lagins Cr. trib. $\times 10^3 m^3$	%	Mountain Creek $\times 10^3 m^3$	%
Slow mass movement								
Soil creep and tree throw	1.7-4.1	40-34	2.3-5.7	41-35	3.2-8.1	37-33	7.6-19.0	37-32
Rapid mass movements								
LANDSLIDES	1.2-1.8 (3.9-6.2)	29-15	1.4-2.2 (3.5-5.7)	25-14	2.8-4.5 (3.7-6.0)	33-18	7.1-11.3 (7.6-12.1)	34-19
Slide scars	0.1-0.3 (0.2-0.9)	2-3	0.1-0.3 (0.2-0.9)	2	0.2-0.9 (0.3-1.2)	2-4	0.9-3.6 (1.0-3.9)	4-6
Hillslope surface								
Slope wash	0.4-1.1	10-9	0.6-1.6	11-10	0.8-2.1	9	1.5-3.8	7
Roads	-		-		-		-	
Stream banks	0.8-4.6	19-39	1.2-6.3	21-39	1.6-8.9	19-36	3.8-20.9	18-36
TOTAL								
Extreme range	4.2-11.9 (0.2-0.9)		5.6-16.1 (0.2-0.9)		8.6-24.5 (0.3-1.2)		20.9-58.6 (1.0-3.9)	
Most probable range	5.8-10.3 (9.4-14.5)		7.7-14.0 (10.7-17.3)		12.0-21.1 (13.3-22.6)		29.1-50.4 (29.9-51.3)	

TABLE 4. (Continued)

B. Since logging[b]

Sediment source[c]	Armentières Cr. $x10^3 m^3$	%	Mosquito Cr. trib. $x10^3 m^3$	%	Lagins Cr. trib. $x10^3 m^3$	%	Mountain Creek $x10^3 m^3$	%
Slow mass movement								
Soil creep and tree tree throw	1.2-3.1	4-6	1.6-4.0	6-7	1.2-2.9	3-4	4.4-11.0	13-15
Rapid mass movements								
LANDSLIDES	20.7-33.1 (31.5-50.4)	75-64	6.5-10.4 (7.8-12.4)	23-19	0.3-0.4 (0.3-0.5)	1	3.6-5.8 (33.5-53.5)	10-8
Slide scars	1.2-4.8 (1.8-7.3)	4-9	0.4-1.6 (0.5-1.9)	1-3	Nil-0.1 (Nil-0.1)	0-1	0.5-1.9 (4.3-17.2)	1-3
Hillslope surface								
Slope wash	0.5-0.9	2	0.7-1.2	2	0.4-0.8	1	1.1-2.3	3
Roads	-		-		-		-	
Road surface	0.2-0.5	1	3.1-5.8	11-10	3.3-6.1	10-8	1.2-2.6	4-3
ROAD BRIDGE	-		1.3-1.6	4-3	minor		-	
STREAM BANKS	4.0-9.2	14-18	15.1-31.8	53-56	28.8-60.2	85	23.6-49.2	69-68
TOTAL								
Extreme range	17.8-51.6 (39.2-71.4)		28.7-56.4 (30.1-58.7)		34.0-70.5 (34.0-70.6)		34.4-72.8 (68.1-135.8)	
Most probable range	32.7-46.7 (45.1-65.5)		33.8-51.3 (35.5-53.3)		36.5-68.0 (36.5-68.1)		40.3-66.9 (84.1-119.8)	

TABLE 4. (Continued)

Sediment source[c]	Armentières Cr. $x10^3 m^3$	%	Mosquito Cr. trib. $x10^3 m^3$	%	Lagins Cr. trib. $x10^3 m^3$	%	Mountain Creek $x10^3 m^3$	%
Contributing area (km^2) (% of total watershed)	3.8	97	5.4	100	5.8	98	12.1	96

[a] Volumes of total sediment production are in parentheses for rapid mass movement. For other processes it is assumed that the ratio between production and delivery to the stream channel is unity.
[b] Periods of record are given in Table 7.
[c] Measured values are titled in capital letters; values derived from regional representative rates (Table 2) are titled in lowercase letters.

TABLE 5. Sediment delivery to individual wedges in Armentières Creek[a]

A. Prior to logging[b]

Sediment source[c]	Upper wedge $x10^3m^3$	%	Middle wedge $x10^3m^3$	%	Lower wedge $x10^3m^3$	%
Slow mass movements						
Soil creep and tree throw	0.9-2.3	36-33	0.5-1.1	50-38	0.3-0.7	43-32
Rapid mass movements						
LANDSLIDES	0.9-1.4 (2.6-4.6)	36-20	0.2-0.3 (0.7-1.1)	20-10	0.1 (0.3-0.5)	14-5
Slide scars	0.1-0.2 (0.2-0.7)	4-3	Nil-0.1 (Nil-0.1)	0-4	Nil-0.1 (Nil-0.1)	0-4
Hillslope surface						
Slope wash	0.1-0.4	4-6	0.1-0.2	10-7	0.2-0.5	29-23
Roads	-		-		-	
Stream banks	0.5-2.6	20-38	0.2-1.2	20-41	0.1-0.8	14-36
TOTAL						
Extreme range	2.5-6.9 (4.6-10.6)		1.0-2.9 (1.5-3.7)		0.7-2.2 (0.9-2.6)	
Most probable range	3.4-6.0 (6.1-9.1)		1.4-2.5 (2.0-3.2)		1.0-1.9 (1.3-2.2)	

TABLE 5. (Continued)

B. Since logging[b]

Sediment source[c]	Upper wedge $\times 10^3 m^3$	%	Middle wedge $\times 10^3 m^3$	%	Lower wedge $\times 10^3 m^3$	%
Slow mass movements						
Soil creep and tree throw	0.7-1.7	3-4	0.3-0.8	7-9	0.2-0.6	9-13
Rapid mass movements						
LANDSLIDES	13.4-24.6 (23.4-37.4)	73-65	3.7-5.9 (5.6-9.0)	82-68	1.6-2.6 (2.5-4.0)	70-54
Slide scars	0.9-3.6 (1.4-5.5)	4-9	0.2-0.8 (0.3-1.2)	4-9	0.1-0.4 (0.1-0.6)	4-8
Hillslope surface						
Slope wash	0.2-0.3	1	0.1-0.2	2	0.2-0.4	9-8
Roads						
Road surface	0.1	1	Nil-0.1	0-1	0.1-0.2	4
STREAM BANKS	3.7-7.7	18-20	0.2-0.9	5-11	0.1-0.6	4-13
TOTAL						
Extreme range	21.0-38.0 (29.5-52.7)		4.5-8.7 (6.5-12.2)		2.3-4.8 (3.2-6.4)	
Most probable range	24.3-34.7 (33.5-48.7)		5.4-7.8 (7.5-11.2)		2.9-4.2 (3.9-5.7)	
Contributing area (km^2)	1.4		0.7		1.7	

[a] Volumes of total sediment production are in parentheses for rapid mass movement. For other processes it is assumed that the ratio between production and delivery to the stream channel is unity.
[b] Periods of record are given in Table 7.
[c] Measured values are titled in capital letters; values derived from regional representative rate (Table 2) are titled in lowercase letters.

equivalent to a two standard deviation statistical error. The results in Table 4 constitute the input term (I) in a sediment balance based upon the stream channels.

Slow Mass Movements

The processes of soil creep and tree throw occur slowly, but are widespread and essentially continuous. They cannot be practically measured in a synoptic study such as this. Accordingly, to estimate the input by soil creep and tree throw, appropriate rates of movement were obtained from the published results of studies conducted in the Pacific Northwest (see Table 2). These indicate that the net rate of movement is similar on forested and logged slopes, as tree throw becomes negligible while creep rate is approximately doubled following logging. Hence, in this study it is assumed that the combined processes of soil creep and tree throw result in movement of the soil column by 2-5 mm/yr.

Soil creep was assumed to extend down to bedrock or a strongly indurated layer, which occurs at a mean depth of approximately 1 m (Smith 1982). As this depth is quite shallow and the slopes are steep, wet, and unstable, the use of a surface rate of soil creep rather than a depth-integrated rate should not strongly bias the subsequent calculations. At least this will provide a maximum estimate of sediment delivery by these processes.

The combined rate was then applied to the length of stream channel juxtaposed by steep, soil-covered slopes (see Table 6). This excluded those streams that drain from bedrock or snow-covered surfaces above the treeline, and higher-order channels that are bordered by low-gradient footslopes or valley flats.

From the annual rates of sediment delivery, shown in Table 6, the total volumes of sediment delivered between 1933 and logging, and then until 1982 were estimated (see Table 4). Sediments reaching channels upstream of a wedge prior to wedge inception are included

TABLE 6. Annual rates of sediment delivery by soil creep and tree throw

Watershed	Contributing length (m)	Creep and throw input (m^3/yr)
Armentières Cr.		
Upper wedge	8 340	33-83
Middle wedge	3 920	16-39
Lower wedge	2 600	10-26
TOTAL	14 860	60-149
Mosquito Cr. trib.	19 840	79-198
Mountain Cr.	61 180	245-612
Lagins Cr. trib.	22 400	90-224

because stream banks deliver predominantly coarse material (see Section 3.1.3), which is transported episodically and slowly. In summary, slow mass movements appear to account for 30-50% of sediment delivered to channels in undisturbed terrain, but only 3-15% after logging. Since the rate estimated for this process remains constant, this change in proportion is a measure of the effect of logging-related disturbance in the study watersheds.

Rapid Mass Movements

Landslides are episodic events that occur at specific places in the landscape and leave clear evidence of their occurrence. Hence, they can be mapped and measured in a retrospective study. The methods employed in this investigation were outlined in Section 2.1.1.

Our treatment of the locale of deposition and the time scale employed for the inventory of slides require clarification. For Armentières Creek and Mountain Creek, only those slides that entered the creek directly were included in sediment delivery; for Mosquito and Lagins Creek tributaries, material deposited on the footslopes was also included. The rationale for this inconsistency is as follows: in the headwaters of the two latter watersheds, several landslides run out on the short and relatively steep footslopes immediately adjacent to the stream channel. The slide deposits are remobilized by surface erosion processes and subsequently reach the stream channel. In contrast, the headwater channels of Mountain and Armentières creeks are juxtaposed with steep slopes, so that mobilized material invariably reaches the stream channel directly. Footslope deposits are present further downstream in these two watersheds, where the valley floor is wider, but the greatly reduced gradient probably prohibits their subsequent transfer to the stream channel.

Landslides that occurred decades before the development of the sediment wedge are considered as sediment sources for the following reasons. The identification of older landslides from air photos is restricted usually to the largest events, where a large area can be distinguished from the undisturbed surrounds by its vegetation succession, and to headwater sites where recurrent failure or snow avalanching prevents vegetation recolonization. Although most of the fine sediment from such events is transported initially a considerable distance downstream, the coarse fraction is moved at a much slower rate. Hence, the morphologic impact of large and/or headwater landslides may persist for many years after the actual event as the supply of coarse material is depleted episodically and slowly.

The global period for analysis is the 50-year period, 1933-1982. Mountain Creek and Lagins Creek tributary watersheds have slide scars pre-dating the 1933 air photography, and thus whose ages are unknown. They, are not included as sources of sediment.

Although no photos were flown over Lagins tributary in 1982, its headwaters appear in the last two frames of the 1982 Mountain Creek sequence, from which it was observed that no new landslides had occurred since 1976. Because no new slides were found elsewhere in the basin during field investigations, the time scale of landslide analysis was assumed to extend up to 1982. In Armentières basin, only 1500 m^3 of sediment reached the creek from pre-1963 landslides. No landslides prior to 1955 were found in the Mosquito Creek tributary basin, perhaps because of the very poor quality of the 1937-38 air photos.

The rates of landslide erosion in the forested and logged parts of the study watersheds are summarized in Table 7. All slides are included in this table. The frequencies of occurrence of specific failure types are indicated in Table 8. It is apparent that nearly all failures are classified as debris slides, of which more than one-third are gully-related; the remaining failures occurred in undissected terrain ("open" slopes).

Landslide behaviour in these basins is not typical of logged Queen Charlotte Islands basins (see Rood 1984). Pre- to post-logging ratios of sediment production remain modest. In Armentières Creek, the forested area produced more sediment than the clearcut because average slide volume is 4 times larger in the former; Lagins tributary experienced no failures in the low gradient clearcuts. Sediment production rates by landsliding are generally similar to those measured elsewhere in the Pacific Northwest (see Table 2). It is noteworthy that in unlogged terrain, sediment production increased substantially in the post-logging period, and that in all the basins, unlogged areas contributed the preponderance of material to the channel. Again, the generally moderate slopes in the logged areas in these particular basins have prompted the outcome.

Landslides contributed 15-33% of sediment reaching channels in the unlogged basins (see Table 4A), and from 1 to 75% after logging.

TABLE 7. Rates of landslide erosion and sediment transfer to creek before and after logging[a]

Watershed	Watershed condition	Period of record (years)	Total sediment production ($m^3/(km^2 \cdot yr)$)			Sediment input to creek ($m3/(km^2 \cdot yr)$)			Sediment delivery ratio[b] ($m3/(km^2 \cdot yr)$)		
			Unlogged	Logged	Ratio	Unlogged	Logged	Ratio	TSP	SIC	Ratio
Armentières Creek	Pre-logging	30	42	n/a	n/a	13	n/a	n/a	42	13	0.3
	Post-logging	19	607	393	0.6	452	21	0.5	566	370	0.7
Mosquito tributary	Pre-logging	30	29	n/a	n/a	11	n/a	n/a	29	11	0.4
	Post-logging	19	95	112	1.2	87	63	0.7	98	82	0.8
Mountain Creek	Pre-logging	32	26	n/a	n/a	24	n/a	n/a	26	24	0.9
	Post-logging	17	178	518	2.9	25	5	0.2	211	23	0.1
Lagins tributary	Pre-logging	36	23	n/a	n/a	18	n/a	n/a	23	18	0.8
	Post-logging	13	6	Nil	Nil	5	Nil	Nil	5	4	0.8

n/a: Not applicable.

[a] Volumes refer to the entire watershed, hence are not simply comparable with the results in line 2 of Table 4.
[b] TSP: Total sediment production from entire (logged and unlogged) watershed;
SIC: Sediment input to creek from entire (logged and unlogged) watershed.

TABLE 8. Failure types and source area conditions

Watershed	Failure type	Number	Number (%) gully related	Number cut boundary related	Number yarding related	Number cut boundary and gully related	Number yarding and gully related	Number on "open" slopes
Armentières Cr.	Debris slide	49	17 (35)	9	0	4	0	19
	Debris flow	1	0 (0)	0	0	0	0	1
	Debris torrent	1	1 (100)	0	0	0	0	0
Mosquito Cr. trib.	Debris slide	10	4 (40)	4	0	2	0	0
	Debris flow	1	1 (100)	0	0	0	0	0
Mountain Cr.	Debris slide	57	21 (37)	8	7	2	2	17
	Debris torrent	1	1 (100)	0	0	0	0	0
Lagins Cr. trib.	Debris slide	14	1 (7)	0	0	0	0	13

The disparate post-logging behaviour is related to the degree to which the channels are isolated from steep hillsides by low-gradient footslopes or floodplains. Except for Lagins tributary, which has anomalously extensive low-gradient areas, the order of relative importance of landslides after logging varies inversely as drainage basin area. Of the order of 75% of landslide-induced sediment production reached the channels after logging (Table 7) except in Mountain Creek, where most failures in the clearcut areas stopped on footslopes.

Following the initial failure, landslide scars are modified by surface erosion processes (rainsplash, sheetwash, dry ravel, rilling). In Washington, Reid (1981) demonstrated an erosion rate of 1000 - 4000 $m^3/(km^2 \cdot yr)$ from scar surfaces (see Table 2). These values are applied in this study to the scars of landslides that reached the stream channels of Armentières and Mountain creeks, and the footslopes of Lagins and Mosquito Creek tributaries. Reid et al. (1981) observed that 10-year-old landslide scars were largely unvegetated, while in the Queen Charlotte Islands, Smith (1982) found that 50% vegetation cover was reached in 20 years. In this study it is assumed that these secondary erosion processes are active for 20 years, hence the volume of sediment eroded from each scar is 20 000 - 80 000 m^3/km^2 (i.e., 2-8 cm depth of soil loss).

In general, slide scars produce an order-of-magnitude less sediment than the initial failures, and less than 5% of the total volume of sediment delivered to the stream channel (see Table 4A). As scars produce sediment finer than 2 mm (Reid et al. 1981), which can be transported rapidly downstream, their impacts on channel morphology should be ephemeral and insignificant, compared to that of the bed load calibre material introduced by the initial failures.

Hillslope Surfaces

The surface erosion of forested and logged hillslopes is, like slow mass movement, a distributing, continuous process that cannot

easily be measured retrospectively. For this study, annual delivery rates were generated by applying the ranges of representative process rates (see Table 2) to the forested and logged basin areas that are adjacent to, and upstream of, the sediment wedges. The total volume of sediment delivered between 1934 and 1982 was then estimated (see Table 4).

Slope wash, like road surface and slide scar erosion, mobilizes only fine sediments. The process accounts for of order 10% of sediment delivery in undisturbed terrain, and yielded of order 1% of sediment into the channels of the study basins after logging.

Road Surfaces

To calculate these values, the road area was measured from air photos (see Section 2.1.3) and appropriate rates of erosion were chosen from the literature (see Table 2). Only those sections of road that intersected the creek upstream of or along a sediment wedge were included in the analysis. The time periods over which the different rates of erosion were employed are given in Table 9.

The collapse of a bridge crossing in the Mosquito Creek tributary delivered approximately 1475 ($\pm$135) m^3 of predominantly coarse material directly into the stream channel (see Table 4). Overall, it is estimated that roads contributed from 1 to 15% of sediment delivered to the study creeks after logging. The range depends upon local terrain, engineering, and intensity of development.

The morphologic impact of sediment eroded from road surfaces may be insignificant, as the fine (less than 2 mm) sediment produced (Reid 1981; Reid *et al.* 1981) is probably transported rapidly through the fluvial system. Moreover, impacts on fish habitat may be less than those experienced elsewhere in the Pacific Northwest, because the road densities in other areas are more than twice those in the study watersheds. For example, Reid (1981) expected a final road density of 2.5 km/km^2 in the Clearwater basin, Washington, and

TABLE 9. Duration of different rates of road surface erosion

Watershed	Period of time at erosion rate ($m^3/[km^2$ road·yr$]$)[a]		
	10 000 - 15 000 (during use)	1000 - 2000 (first year disused)	100 - 500 (abandoned)
Armentières Cr.			
Upper wedge	1967-1969	1970	1971-1982
Middle wedge	1967-1969	1970	1971-1982
Lower wedge	1962-1965	1966	
	1967-1969	1970	1971-1982
Mosquito Cr. trib.	1963-1969	1970	1971-1982
Mountain Cr.	1965-1967	1968	1969-1982
Lagi.. Cr. trib.	1970-1977	1978	1979-1982

[a] Erosion rates given in Table 2.

Swanson and Dyrness (1975) assumed that roads would eventually cover 8% of an Oregon watershed. In the study watersheds, road densities and coverage are less than 1.0 km/km^2 and 1%, respectively.

Stream Banks

The rate of stream bank erosion was measured from sequential air photography (see Section 2.1.2), and the results are summarized in Table 10. The reaches were determined by distinctive changes in channel morphology. Armentières Creek was subdivided into three reaches, each containing a sediment wedge. Mosquito Creek tributary had the wedge in its most downstream reach, a haul road constructed along the edge of a stream bank in reach A, and a change of surficial materials (from fluvial to fluvial/colluvial) in the most upstream reach (B). Mountain Creek is broken into four reaches: the reach

TABLE 10. Measurements of changes in stream channel widths

Watershed	Date(s)	Mean channel width (m) and % change[a] (upstream direction ------>)		
Armentières Cr.		Lower wedge	Middle wedge	Upper wedge
			Mean channel width (m)	
	1933	32.0	23.2	34.1
logged 1962-65 ----->	1964 ----->	39.7	33.4	30.0
1976-69 ----->	1976 ----->	26.4	-----> 29.0	------> 44.3
	1982	30.7	24.0	34.8
			% change	
	1933-64	+24.1	+44.0*	-12.0
	1964-76	-33.5*	-13.2	+47.7
	1976-82	+16.3	-17.2	-21.4
	n[b]	11	14	7
Mosquito Cr. trib.		Wedge	Reach A	Reach B
			Mean channel width (m)	
logged 1963-69 ----->	1964 --->	20.3	25.2	23.6
	1976	33.2	24.0	21.0
	1982	27.3	25.7	20.8
			% change	
	1964-76	+63.5*	-4.8	-11.0
	1976-82	-17.8*	+7.1	- 1.0
	n	42	16	11

TABLE 10. (Continued)

Watershed	Date(s)	Mean channel width (m) and % change[a] (upstream direction ------)			
Mountain Cr.		Reach A	Wedge	Reach B	Reach C
		Mean channel width (m)			
	1933	22.5	20.3	24.7	24.3
logged 1965-67 --	1976 -----	48.2 -----	40.9	25.0	14.7
	1982	33.2	32.9	17.2	13.1
		% change			
	1933-76	+114.2*	+101.5*	+ 1.2	-39.5*
	1976-82	- 31.1*	- 19.6*	-31.2*	-10.9
	n	19	27	38	22
Lagins Cr. trib.		Reach A	Wedge	Reach B	Reach C
		Mean channel width (m)			
	1966	34.0	57.4	56.3	30.4
logged 1970-77 --	1976 -----	27.4 -----	58.4 ---	49.7	27.6
		% change			
	1966-76	-19.4	+1.7	-11.7	-9.2
	n	7	36	7	44

* significant change at the = 0.05 level in a paired t-test.

[a]See text for details of reach delimitations. Arrows indicate reaches that may have been affected by logging in the period noted.
[b]n = number of measurements in the reach.

that contains the sediment wedge separates the downstream reach (A) from reach B and the most upstream reach (C), in which the channel pattern is controlled by bedrock. Similarly, in Lagins Creek tributary the sediment wedge defines the upstream limit of reach A and the downstream limit of reach B; the most upstream reach (C) begins at the clearcut boundary, and indicates the rate of stream bank erosion in the forested part of the watershed.

It is apparent from Table 10 that most of the channel width increase (i.e., stream bank recession) occurred in the sediment wedge reach sometime before 1976, and that the channels narrowed between 1976 and 1982. Stream bank erosion apparently contributed 20-40% of sediment to the channels before logging; afterward, it became the dominant source in all but Armentières Creek (Table 4B), contributing more than half the total load in three cases.

Armentières Creek merits attention on several issues. Channel width decreased significantly along the lower wedge reach and increased significantly along the middle wedge reach (see Table 10). The former is the result of rapid recolonization by streamside vegetation (e.g., red alder), while the latter appears to be due chiefly to the inaccurate delineation of the forested stream banks on the 1933 air photos. The upper wedge experienced the largest absolute (14.3 m) and relative (+47.7%) change in channel width between 1964 and 1976. Only this change corresponds with that expected from logging activities. However, because of the few degrees of freedom, it was not statistically significant. Consequently, other changes that were not statistically significant were reviewed for their possible geomorphic significance. After these considerations, the eroded stream bank material from only the upper wedge reach was used in sediment source computations for Tables 4 and 5.

Mosquito Creek tributary presents few problems because the changes that are not statistically significant are small enough to be

the result of measurement inaccuracies. The significant decrease in sediment wedge width between 1976 and 1982 is due largely to the colonization by red alders along the lowermost 270 m of the channel (i.e., downstream of where the bridge collapsed and the flow was diverted along a haul road). Bank retreat along the wedge reach between 1964 and 1976 is the only source of stream bank material used in sediment delivery calculations.

Several significant changes in width are apparent in the analysis of Mountain Creek (see Table 10). The sediment wedge reach doubled its width from 1933 to 1976, but narrowed thereafter. An even greater increase and subsequent decrease in width were measured for the reach downstream of the wedge, where in-stream skidding was practised. In both the above reaches, and also reach B, the significant decrease in width between 1976 and 1982 is the result of rapid colonization by streamside vegetation. In contrast, reach C is a narrow, bedrock-controlled stream channel, and the apparent 40% decrease in width between 1933 and 1976 reflects the inadequacy of using tree crowns to represent the stream bank margins of small channels. Thus, the only riparian sediments considered to contribute to the wedge were those derived from the stream banks adjacent to the wedge between 1933 and 1976.

Lagins Creek tributary did not widen or narrow significantly in any reach between 1966 and 1976. However, the reach containing the wedge in 1976 is a section of a logging road along which the creek was diverted and, therefore is not comparable to the undisturbed, 1966 stream channel. A better indication of the amount of wedge sediment contributed by stream bank erosion is the difference between the initial road width and its width following river avulsion. The latter was obtained from the wedge reach, and the former from measurements on the 1976 air photos of roads unaffected by flow diversion. The rate of bank retreat adjacent to the road was calculated using these data. In 1982, field surveys indicated that the channel had narrowed by 50.3% since 1976 because of the growth of red alder on the surface of the sediment wedge.

To calculate the volume of sediment introduced through stream bank erosion, the areal rates of bank retreat were multiplied by the mean height of the stream banks measured in the field (see Table 11).

TABLE 11. Mean stream bank heights

Watershed	Mean height (m)
Armentières Cr.	1.0
Mosquito Cr. trib.	0.9
Mountain Cr.	1.4
Lagins Cr. trib.	1.3

The edges of the stream banks as delineated from air photos do not account for the volume of material eroded from beneath overhangs. This volume was calculated from field measurements of undercuts and overhangs along the stream banks. However, the values were not included as part of the stream bank inputs in Table 4, because they are of the same order of magnitude as the measurement uncertainties in air photo analyses and, therefore, represent an unjustified refinement of the estimate of total riparian sediment input.

3.1.2 Sediment storage

The volume of material stored in the sediment wedges defines the storage component of the sediment budget.

The surface of a sediment wedge is described by the longitudinal profile. Between bedrock control points, its base is assumed to be a smooth concave curve, based on the widespread observation that stream profiles are usually concave over considerable distances (Mackin 1948; Hack 1957; Miller 1958). Bedforms, such as pool-riffle

sequences, create only local gradient variations (Richards 1982, p. 223). The mathematical function that best fits the surveyed points upstream and downstream of the depositional zone and the bedrock outcrops along the sediment wedge was found by attempting logarithmic, power, and polynomial curve fits. The long profiles and best-fit curves of each sediment wedge are shown in Figures 4.

The volume of a sediment wedge was estimated by measuring its length and depth from the long profile plots and obtaining widths from air photos (see Section 2.1.2). Each wedge was divided into sub-units with a 50-m base length, and the mean values of width and depth for each sub-unit were used to compute their individual volumes. The sum of these increments equals the total volume of the sediment wedge:

$$S_t = \sum_{u=1}^{u=n} W_u D_u L_u$$

where S_t = total volume of the sediment wedge (m^3)

u = sub-unit number

n = maximum number of sub-units

W_u = mean width of sub-unit (m)

D_u = mean depth of sub-unit (m)

L_u = length of sub-unit (50 m)

This procedure calculates the volume of a rectangle, although most stream channels are more semi-circular or trapezoidal in cross-section. Two shape adjustments are illustrated in Figure 5 and given in Table 12. Column B indicates semi-circular sediment wedge volumes and column C gives the appropriate volume reduction for stream bank materials at the angle of repose (35°) for unconsolidated sands and gravels. Moreover, if the creek is incised into the sediment wedge (Figure 5B), the volume occupied by the stream channel should be deducted. Volumes estimated from field observations

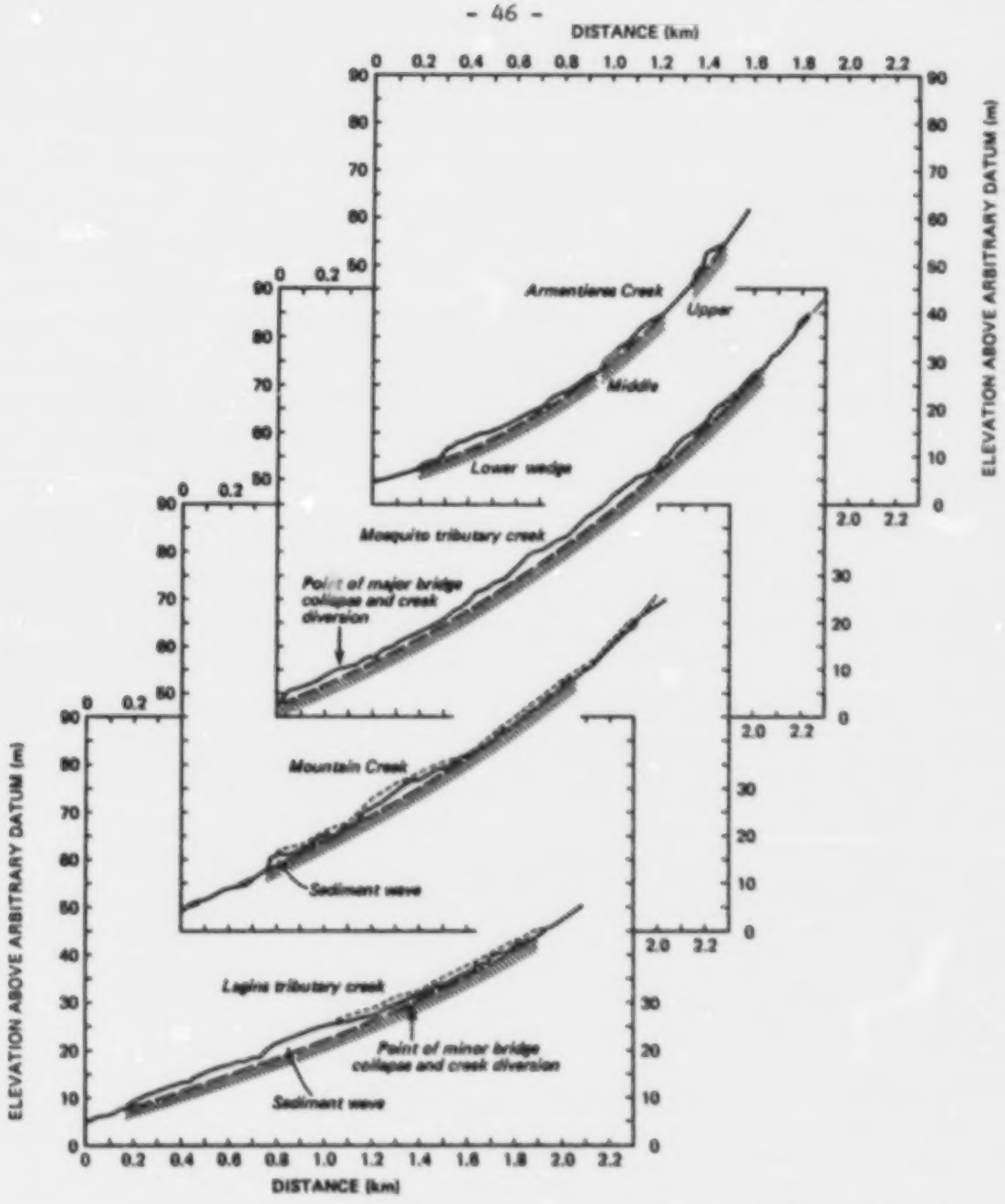


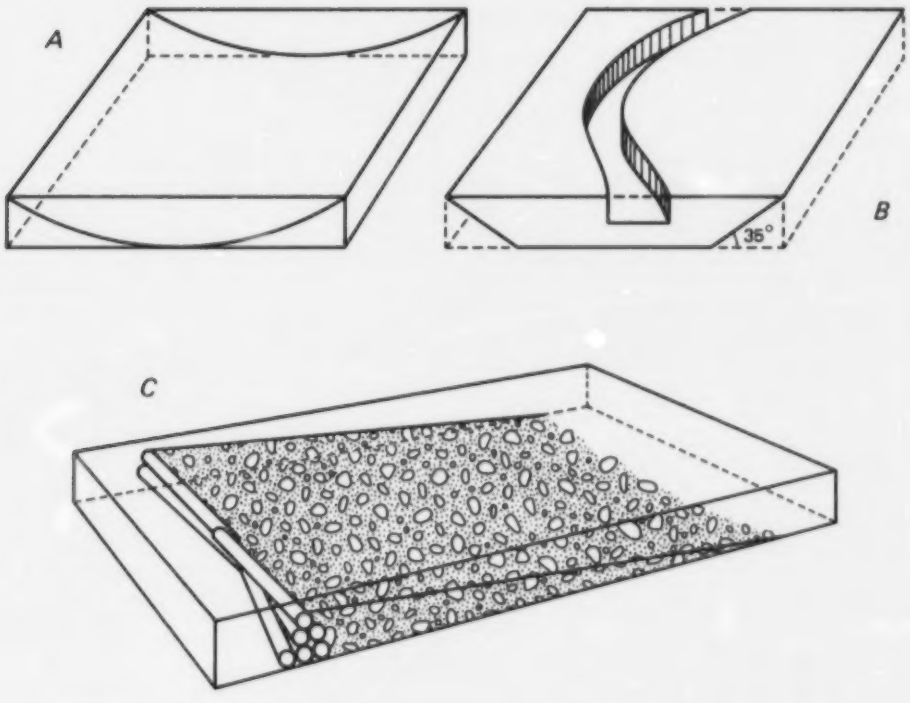
FIGURE 4. Long profiles of sediment wedges in the study creeks. The solid line is the extant long profile along the regular aggradational surface; the dashed line represents a mathematically fitted smooth long profile to approximate the channel bed under the wedge; cross hatching represents the longitudinal extent of wedge sediments; pecked line represents terrace surface.

TABLE 12. The estimated volume of sediment stored in the sediment wedges[a]

Watershed	Sediment wedge			A[b]	B[b]	C[b]	D[b]	E[b]	F	G
	Length	Mean width	Mean depth	Rectangular wedge volume	Semi-circular wedge volume	Triangular subtraction volume	Stream channel volume	Antecedent storage volume	Sediment volume B-D-E	Wedge estimates A-C-D-E
	(m)	(m)	(m)	($x10^3m^3$)	($x10^3m^3$)	($x10^3m^3$)	($x10^3m^3$)	($x10^3m^3$)	($x10^3m^3$)	($x10^3m^3$)
Armentières Cr.										
Upper wedge	160	35	1.6	9.0	6.2	0.6	0.6	0.2-0.3	5.3-5.4	7.5-7.6
Middle wedge	300	27	1.2	9.4	6.9	0.6	0.5	0.2-0.4	6.0-6.2	7.9-8.1
Lower wedge	770	22	1.5	25.3	16.8	2.5	1.4	0.7-1.5	13.9-14.7	19.9-20.7
TOTAL				43.7	29.8	3.7	2.5	1.1-2.2	25.1-26.2	35.3-36.4
Mosquito tributary	2050	28	1.7	99.9	57.0	8.5	8.6	1.2-2.5	45.9-47.2	80.3-81.6
Lagins tributary	1650	16	1.5	40.0	28.1	5.3	7.5	1.7-3.4	17.2-18.9	23.9-25.5
Mountain Creek	1300	36	0.8	39.5	29.0	1.2	3.9	0.8-1.6	23.5-24.3	32.8-33.6

[a] Based on 1983 long profile surveys, and widths derived from 1976 air photographs.

[b] See Figure 5.



A. Rectangular and circular arc sections (A and B in Table 12) based upon survey of the wedge surface and cross-section assumptions.

B. Trapezoidal section based on the subtraction of a triangular volume at each bank to represent a repose angle slope for non-cohesive, granular material (A-C in Table 12), and stream channel volume (D in Table 12).

C. Debris accumulation behind a log step: representative volumes are drawn from Hogan (1986) (E in Table 12).

FIGURE 5. Geometry of a sediment wedge and normal in-channel sediment storage.

for stream channels with a rectangular cross-section are presented in Table 12 (column D). Further reduction of sediment wedge volumes is possible if bedrock intrudes into the smooth, concave pre-wedge profiles. Unfortunately, apart from the adjustments made already for bedrock outcrops, there is no basis for an objective evaluation of bedrock micro-topography. Finally, the volume of material stored behind log jams or other in-stream obstructions prior to the development of the sediment wedges should be subtracted from the contemporary wedge volumes. Hogan (1986) found the mean volume of sediment stored behind in-stream obstructions in channels in forested watersheds on the Queen Charlotte Islands to be 0.03-0.06 m^3/m^2 of channel area. The volumes of antecedent storage were estimated by applying this value to the length of each sediment wedge (see Table 12, column E).

Therefore, a range of possible sediment wedge volumes exists, depending on channel shape, stream incision, and antecedent storage factors. In Table 12, columns F and G indicate two possible volumetric estimates, and the actual wedge volumes probably lie within this range.

3.1.3 Sediment mobility

This section discusses the mobility of the material in the sediment wedges, and presents the output term in the sediment budget equation in terms of downstream sediment transport. As the rate of sediment discharge was not measured directly in the field, the output is inferred from the estimated input and storage volumes and measured sedimentological and morphological parameters.

Character of Sediments

Plots of wedge surface, wedge subsurface, and stream bank sediment samples are shown in Figure 6 and their associated grain-size statistics are summarized in Table 13.

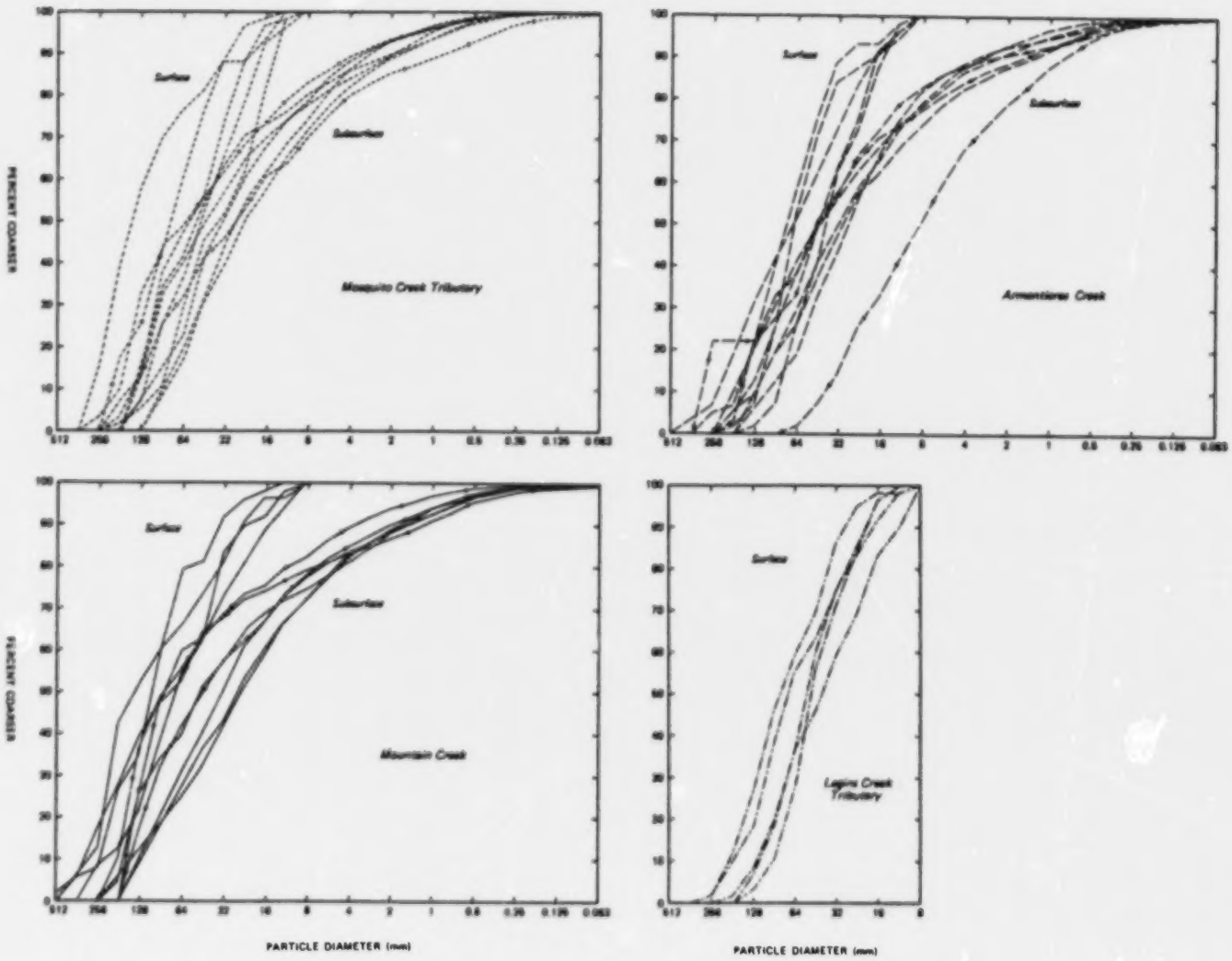


FIGURE 6. Particle size distributions of "sediment wedge" and stream bank material: Stream bank material indicated by small circles.

TABLE 13. Grain-size statistics for wedge surface, wedge subsurface, and stream bank sediments

Watershed	Site No.	Dist.[b]	Geometric mean (mm)			Mean (phi)[a]			Standard deviation (phi)[a]		
			Surface	Sub-surface	Bank	Surface	Sub-surface	Bank	Surface	Sub-surface	Bank
Armentières Cr.	1	1700	66.3	25.8	43.4	-6.05	-4.69	-5.44	1.50	2.10	2.76
	2	1510	73.5			-6.20			1.14		
	3	1270	60.5	31.3		-5.92	-4.97		1.02	2.42	
	4	930	45.9	20.7	29.2	-5.52	-4.37	-4.87	1.26	2.53	2.54
	5	600	37.3	23.3	6.8	-5.22	-4.54	-2.76	1.01	1.99	2.19
Mosquito Cr. trib.	1	1990	113.8			-6.83			1.24		
	2	1580	56.5	20.7		-5.82	-4.37		1.08	1.95	
	3	1220	46.5	27.7	19.3	-5.54	-4.79	-4.27	1.14	2.40	2.76
	4	940	35.3	17.1		-5.14	-4.10		1.13	2.16	
	5	720	78.2	25.3	43.1	-6.29	-4.66	-5.43	1.17	2.03	2.30
	6	540		32.2			-5.01			2.34	
Mountain Cr.	1	1630	112.2	19.8		-6.81	-4.31		1.25	2.37	
	2	1300	69.6	27.3	32.4	-6.12	-4.77	-5.02	1.27	2.61	2.66
	3	1000	76.6	20.3	29.0	-6.26	-4.34	-4.86	1.72	2.47	2.41
	4	670	86.8	22.9	45.6	-6.44	-4.52	-5.51	1.41	2.40	2.26
Lagins Cr. trib.	1	1750	76.6			-6.26			1.09		
	2	1300	60.5			-5.92			1.29		
	3	1000	50.2			-5.65			1.01		
	4	600	39.1			-5.29			1.26		
	5	200	44.9			-5.49			0.90		

[a] phi = $-\log_2(\text{mm})$, represents a logarithmic transformation of grain size data. It is commonly employed in sedimentological studies to eliminate the skew toward the coarse end of the size distribution that appears in the untransformed data.

[b] Distance upstream from beginning of the long profile (see Figure 4).

The mean size of the surface material is greater than that of the underlying sediments; the latter are always classified as gravels, while the former are gravels and/or cobbles (e.g., Mountain Creek). Bank sediments are of gravel grade, but the size range is greater than that present in the subsurface sediments, reflecting the presence of a greater proportion of fine material in the banks than in the streambed. The standard deviations indicate that subsurface sediments are commonly sorted as well as or better than the bank material, but that both are very poorly sorted in comparison with the surface sediments.

With these statistical parameters, surface sediments can be discriminated from underlying material, but the latter cannot be distinguished readily from stream bank sediments. These observations reflect the greater extent to which the surface sediments have been fluvially reworked, as compared to the subsurface and bank material. As the surface sediments represent a layer only one grain in thickness, the underlying material is a better indicator of the source and the extent of reworking of the wedge deposits. However, the threshold of wedge sediment transport is controlled by the surface grains, because only after their mobilization can the underlying material be fluvially re-sorted.

The similar grain size characteristics of bank and subsurface sediments suggest that the latter may be derived largely from the former with little fluvial reworking. Even when the subsurface and bank samples are truncated at 64 mm (-6 phi) so the details at the fine end of the distribution can be examined, the resultant cumulative curves emphasize their similar fines content. In each creek, however, the finest-textured sample was obtained from the stream banks. The rapid introduction of a large volume of material and the development of an armoured surface layer would prevent the efficient flushing of fines from the wedge deposits by normal fluvial processes.

Due to the limited number of sediment samples analyzed, it can not be shown from sedimentary evidence alone that stream banks are the principal source of the wedge deposits; for example, landslide deposits may have a similar grain size distribution (they were not sampled directly). In Armentières Creek, the subsurface wedge sediments, which were derived chiefly from landslides (see Table 5), and the alluvial stream bank deposits (except for the atypically fine-textured distal sample) had similar grain size distributions (see Table 13). The sedimentary evidence is consistent with the conclusions drawn in Section 3.1.1 that stream banks are the single most important sediment source in Mountain Creek, Mosquito tributary, and Lagins Creek tributary.

The mode of fluvial sediment transport depends largely on particle size, with material finer than 1-2 mm representing suspended load and the coarser fraction moving as bed load. Approximately 90% of the wedge subsurface sediments are coarser than 2 mm, and 94% are coarser than 1 mm. The stream bank material exhibits only fractionally lower cumulative totals at these sizes (see Table 14). Hence, as more than 90% of the wedge material is of bed load calibre, the mobility of a sediment wedge is determined primarily by bed load transport, which occurs only sporadically.

Bed sediments are coarse-textured and therefore highly pervious. Because the cross-sectional area of wedge deposits is substantially greater than that of the stored fluvial sediment in an undisturbed channel, there is a corresponding increase in subsurface water flow through the sediments. It was observed during late summer than the entire stream flow may be abstracted into the subsurface at places along the sediment wedges, leaving only unconnected pools of standing water on the surface for periods of up to several weeks.

Inputs/Storages

Sediment output can be quantified indirectly as the difference between the estimated input and storage volumes. Hence, Table 15

TABLE 14. Proportion of sub-surface and stream bank material coarser than 1 mm and 2 mm

Watershed	Mean % coarser than 1 mm		Mean % coarser than 2 mm	
	Subsurface	Banks	Subsurface	Banks
Armentières Cr.	94.5	90.7	90.9	85.6
Mosquito Cr. trib.	94.8	92.5	90.6	89.1
Mountain Cr.	93.0	93.7	88.2	89.9
Mean	94.1	92.3	89.9	88.1

gives the volumetric differences between the ranges of sediment inputs (from Table 4) and storages (from Table 12), and the mean annual rate of sediment transport before and after logging.

The pre-logging sediment budget is completed on the assumption that storage volumes in the channels were not changing. Output is estimated to be of order $10^2 m^3/yr$ in the three smaller watersheds, and $10^3 m^3/yr$ in Mountain Creek. The unit area sediment yields are consistent, being 33-67 $m^3/(km^2 \cdot yr)$ in the small watersheds and 50-100 $m^3/(km^2 \cdot yr)$ in Mountain Creek. This is less remarkable than it appears since, in the pre-logging period, only landslide sources -- accounting for 15-33% of the sediment delivered -- were individually measured.

After logging, sediment output varied markedly amongst the basins, according to local conditions. In Armentières Creek and Mosquito tributary, the volumetric ranges of the sediment wedges overlap those of the sediment inputs, implying a very low rate of sediment transport. This is corroborated by the absence of terraces along these creeks, which suggests that negligible stream

TABLE 15. Volumes and rates of sediment input, transport, and storage in the streams[a]

A. Prior to logging

Watershed	Sediment input Volume ($\times 10^3$ m^3)	Sediment stored in wedge reach[b] ($\times 10^3$ m^3)	Sediment transport[c] (m^3/yr)	Sediment transport[c] (tonnes/yr)[d]	Sediment "residence" time[e] year
Armentières Cr.:					
Upper wedge	3.4-6.0 (2.4-4.7)	0.2-0.3	110-200 (80-160)	200-360 (140-280)	1-3 (1-4)
Middle wedge	1.4-2.5 (1.0-2.0)	0.2-0.4	160-280[f] (110-230)[f]	290-510[f] (200-400)[f]	1-4[f] (2-6)[f]
Lower wedge	1.0-1.9 (0.5-1.3)	0.7-1.5	190-340[f] (130-270)[f]	350-620[f] (230-480)[f]	3-12[f] (4-15)[f]
TOTAL	5.8-10.3 (3.9-8.0)	1.1-2.2	190-340 (130-270)	350-620 (230-480)	3-12 (4-15)
Mosquito Cr. trib.	7.7-14.0 (5.3-10.8)	1.2-2.5	260-470 (180-360)	460-840 (320-650)	3-10 (3-13)
Lagins Cr. trib.	12.0-21.1 (8.0-16.0)	1.7-3.4	330-590 (220-440)	600-1060 (400-800)	3-10 (3-14)
Mountain Cr.	29.1-50.4 (19.3-37.9)	0.8-1.6	910-1580 (600-1180)	1640-2480 (1090-2130)	0.5-2 (0.5-2)

TABLE 15. (Continued)

B. After logging

Watershed	Sediment Input Volume ($\times 10^3$ m^3)	Sediment stored in wedge[g] ($\times 10^3$ m^3)	Sediment transport[c] ($\times 10^3$ m^3)	(m^3/yr)	(tonnes/yr)[d]	Sediment "residence" time[e] year
Armentières Cr.:						
Upper Wedge	24.3-34.7 (14.9-21.5)	5.3-7.6 (4.8-6.8)	16.7-29.4 (8.1-16.7)	900-1500 (400-900)	1600-2800 (750-1600)	4-8 (5-17)
Middle Wedge	5.4-7.8 (3.1-4.6)	6.0-8.1 (5.4-7.3)	14.0-31.2[f] (7.3-16.7)[f]	700-1600[f] (400-900)[f]	1300-2950[f] (700-1600)[f]	4-12[f] (6-18)[f]
Lower Wedge	2.9-4.2 (1.5-2.4)	13.9-20.7 (12.5-18.6)	Nil-21.5[f] (Nil-6.6)[f]	Nil-1100[f] (Nil-350)[f]	Nil-2000[f] (Nil-650)[f]	13[f] 19[f]
TOTAL	32.7-46.7 (19.5-28.5)	25.1-36.4 (22.6-32.8)	Nil-21.6 (Nil-5.9)	Nil-1100 (Nil-300)	2050 (<550)	23 (>75)
Mosquito Cr. trib.	33.8-51.3 (22.3-37.7)	45.9-81.6 (41.3-73.4)	Nil-5.4 (Nil)	Nil-300 (Nil)	500 (Nil)	150 (>150)
Lagins Cr. trib.	36.5-68.0 (28.0-56.3)	17.2-25.5 (15.5-23.0)	11.0-50.8 (5.0-40.8)	800-3900 (400-3100)	1450-7000 (700-5650)	4-32 (5-58)
Mountain Cr.	40.3-66.9 (30.6-54.4)	23.5-33.6 (21.2-30.2)	6.7-43.4 (0.4-33.2)	400-2600 (20-2000)	700-4600 (50-3500)	9-84 (11-1500)

[a] Values in parentheses refer to bed load calibre material only.
[b] Antecedent storage volume (E) of Table 12: see text for discussion.
[c] For period of record, see Table 7. In part A, Transport = Input; in part B Transport = Input - Sediment stored in wedges.
[d] Based on 1.8 tonne/m^3.
[e] Sediment stored in channel/sediment transport per year.
[f] Includes the volume ofsediment exported from upstream reaches.
[g] From Table 12.

downcutting and, hence, sediment export has occurred. In Mountain Creek and Lagins tributary transport rates of order $10^3 m^3$/yr are not greatly changed from pre-logging totals. These results, together with the large influx of sediment to the channels, mean that sediment "residence time" has increased from order years to order decades (Table 15). Thus, the sediment wedges in which most of the sediment is stored may persist for a long time.

Within Armentières Creek, the volume of material transferred between the three sediment wedges was used to estimate local rates of sediment transport (see Table 15B). After logging, the upper wedge reach received 16 700-29 400 m^3 more sediment than it stored, producing an estimated mean annual output of 900-1500 m^3. As the middle wedge reach has comparable input and storage volumes, it acts as a transportation conduit for upstream sediments, delivering upper wedge material to the lower wedge reach. Of this amount, 9700-17 800 m^3 contributed to the development of the lower wedge, so that as little as zero or as much as 21 500 m^3 could be transported further downstream. The latter range implies a mean annual sediment export rate (since 1965) between 0 and 1100 m^3/yr, less than 350 m^3 of which would be of bedload calibre.

Estuarine sedimentation at the mouths of Mountain, Lagins and Armentières creeks was also examined from hydrographic charts and air photos. No evidence of aggradation was found and therefore it is concluded tentatively that an insignificant volume of bed load reaches the estuaries. In Armentières Creek, for example, the 5900 m^3 of sediment exported from the lower wedge, whose terminus is 180 m from the mouth of the creek, would result in an average estuarine progradation of only 2 mm/yr.

Analysis of Sediment Accumulations

Along the sediment wedges in Mountain Creek and Lagins Creek tributary are discontinuous and unpaired terraces. The heights of

these terrace levels above the surface of the sediment wedges were measured during field surveys, and linear interpolation between points facilitates the delineation of the terrace "profiles" on Figure 4. The volumetric differences between present wedge profiles and their terrace "profiles" are estimated with the procedure described in Section 3.1.2.

Observations from air photos and consideration of the mode of bed load transport suggest that the terrace surfaces were produced episodically by the slow, downstream movement of sediment "waves" (see Figure 4), and are not the remnants of a single episode of aggradation. Consequently, much of the coarse sediment present in the downstream wedges originates from stream incision and terrace formation in the upstream alluvial deposits.

This is demonstrated in Mountain Creek if the most downstream wedge reach (350-800 m in Figure 4) is compared with the adjacent upstream reach (800-1200 m in Figure 4). In 1982, the lower reach held a wedge volume of approximately 11 100 m^3, and since 1976 (which, from air photo evidence, appears to be the year of maximum aggradation) a further 9500 m^3 had been exported. This corresponds to a mean bed load transport rate of 1600 m^3/yr. Hence, the lower reach contained 20 600 m^3 of sediment in 1976, of which 11 200 m^3 is accounted for by the erosion of adjacent stream banks, and the remaining volume (9400 m^3) is assumed to be bed load delivered from the upstream reach (see Table 16).

The volumetric difference between the wedge and terrace profiles in the upstream reach indicates that 19 000 m^3 of sediment has been exported from there (Table 16). This discrepancy between the assumed output (9400 m^3) and apparent output (19 000 m^3) volumes can be explained in terms of the episodic and wave-like nature of bed load transport. By travelling downstream in a series of aggradation/incision phases, a single sediment "wave" can leave a sequence of terraces along the stream, identical to those that would

be produced by a single, stream-length aggradation/incision episode. Put another way, the "full" wedge volumes implied by the terraces probably never were present. Air photo analyses indicate that in 1976, two "waves" of sediment were present in Mountain Creek: one in the lower reach and the other along part of the upstream reach (800-900 m in Figure 4). From these observations, it appears that the terraces found along the upper reach were produced by a series of sediment "waves", and thus the total volume of material exported is less than the estimated 19 000 m^3.

In Lagins Creek tributary, the same procedure is used to quantify the sediment transfers along the length of the entire wedge. Four reaches can be distinguished morphologically: the most downstream reach (150-700 m in Figure 4) developed a wedge after the 1976 winter storm had diverted the creek along the haul road in the

TABLE 16. Volumes of intra-wedge sediment transfers[a]

Watershed	Reach (m)	Wedge volume (m^3)		Sediment input (m^3)	
		Present	Removed	Banks	Bed load
Mountain Cr.	350-800	11 100	9 500	11 200	9 400*
	800-1200		19 000		
Lagins Cr. trib.	150-700	15 800		5 700	10 100*
	700-1400		7 000		
	1400-1700	4 600	1 900*	6 500	
	1700-1850		1 900		
			10 800		

* Values derived by arithmetic difference between the values estimated from survey (see text for further discussion).
[a] All values rounded to the nearest 100 m^3.

adjacent and the most upstream reaches (700-1400 m, and 1700-1850 m, respectively, in Figure 4). Terraces now occur in the haul road reaches. Air photo observations indicate that sediment has been transported from the three upper reaches into the lower reach since 1976, and quantitative support is given by the estimated volumetric transfers of sediment. In 1982, the lower reach had an approximate wedge volume of 15 800 m^3, of which 5700 m^3 is derived from the erosion of contiguous stream banks; the remaining 10 100 m^3 presumably represents the bed load influx from upstream since 1976, and is equivalent to a mean transport rate of 1700 m^3/yr. This input volume corresponds closely to the estimated volume of sediment exported from the three upstream reaches between 1976 and 1982 (10 800 m^3, or 1800 m^3/yr; see Table 16). Therefore, two-thirds of the coarse sediment present in the lower reach of Lagins Creek tributary was transported rapidly in the form of a bed load "wave" following creek diversion and incision along the upstream haul road. Here, a single episode of upstream incision did occur.

The short-term sediment transport rates derived from morphologic evidence in Mountain Creek (1600 m^3/yr) and Lagins tributary (1700 m^3/yr) are reasonable medians of the rates estimated from input/storage volumes (400-3900 m^3/yr).

In Mosquito tributary, the main bridge crossing collapsed after logging was completed, introducing 1300-1600 m^3 of bed load calibre material (see Table 48) and additional fine sediments into the downstream channel reach. This material has been transported only 270 m (see Figure 4) because of its coarse texture and the diversion of most of the stream flow along a haul road. However, the total volume of sediment presently deposited downstream of the former bridge crossing is estimated to be 2600-4200 m^3. This requires the addition of 1300-2600 m^3 of material, of which 90% represents bed load since the time of bridge collapse. From air photo analyses, it is known that the bridge collapsed sometime between 1964 and 1974.

If it is assumed that the bridge failed in 1969, then the mean bed load transport rate is 100-200 m^3/yr, which is an order of magnitude lower than that found in Mountain Creek and Lagins Creek tributary, but consistent with the results of Table 14.

3.1.4. Summary

From the sediment budget approach, used to assess the input, storage, and output of sediment in the four study watersheds, the following conclusions can be drawn:

1. The most important sediment sources after logging in the study basins are stream banks and landslides, which together account for two-thirds to three-quarters of the sediment inputs (see Table 4).
2. Landslides:
   i. Approximately 65-75% of all sediment mobilized on the slopes (production) reaches the drainage network (delivery).
   ii. Sediment production is higher but sediment delivery is lower in clearcut areas than in forested areas.
   iii. Approximately 35-40% of all landslides are gully-related; none are road-related.
3. Stream Banks:
   i. Statistically significant riparian erosion is restricted to the stream banks flanking each sediment wedge.
   ii. Statistically significant bank retreat occurred only during, and immediately after, logging.
   iii. Stream banks are currently retreating only along reaches that are immediately downstream of the sediment wedges.
4. In each study watershed, the volume of sediment input equals or exceeds the volume in storage. The volumetric difference indicates a recent output rate of order 10^3 m^3/yr from Mountain Creek and Lagins Creek tributary, 10^2 m^3/yr from Armentières Creek, and negligible export from Mosquito Creek tributary; a high proportion of the sediment is transported as bed load.

5. Observations from air photos and in the field suggest that bed load is transported episodically and slowly downstream in a series of sediment "waves". Consequently, much of the downstream wedge material is derived from the erosion and transport of upstream wedge deposits.
6. Morphological evidence indicates intra-wedge sediment transport rates of 1600-1800 m^3/yr in Mountain Creek and Lagins Creek tributary, 500-900 m^3/yr in Armentières Creek, and 100-200 m^3/yr in Mosquito Creek tributary; 90% of this sediment is of bed load calibre.
7. Only in Lagins tributary has sediment output from the basin increased markedly in post-logging time. In all basins, the sharply increased inputs are buffered by the major increase in in-channel storage represented by the sediment wedges. In all but Armentières Creek, excessive bank erosion was the single principal source of the increased input.

3.2 Agents Causing Sediment Wedge Development

Without stream bank retreat, there would be significantly less sediment available to initiate a wedge in three of the four study watersheds and, moreover, insufficient lateral room for wedge development. The factors leading to sediment wedge inception and growth are closely related to those causing stream bank destabilization.

Stream banks may become destabilized by a natural or logging-induced increase in stream flow or stream sedimentation, or as the result of timber harvesting practices. The hydrological changes accompanying logging elsewhere in the Pacific Northwest have been varied, but in cases where stream bank erosion has occurred, high flows *per se* have not been blamed (Rice 1981; Toews and Moore 1982; Lyons and Beschta 1983) -- nor does it appear likely that they are the cause here (see Karanka 1986).

Stream channel aggradation (natural or logging-induced) may destabilize stream banks by creating channel changes that deflect stream

flow against the banks, which are then undercut; the added sediment may enhance aggradation and so the cycle may be repeated. In general, only point sources (namely landslides in the four study watersheds) deliver sufficiently large volumes of sediment to short reaches of channel such that serious, local aggradation is initiated. Non-point sources (e.g., soil creep, slope wash) deliver much less sediment per unit length of stream. As sediment delivery to the study creeks by landslides is lower in clearcut areas than in forested areas (see Table 7), stream sedimentation cannot be attributed to logging activities on hillslopes. The largest landslide identified in the Mountain Creek basin delivered 8300 m^3 of sediment into the stream channel circa 1950, when the basin was unlogged. However, bank retreat and wedge development (observed from air photos) did not occur for 20 years, until after logging. Therefore, stream bank destabilization in the study watersheds is unlikely to result from (natural or logging-induced) increases in stream flow or sediment delivery by hillslope failures.

In contrast, the specific logging practices used in the four study basins, which are discussed in Section 1.3.2 and summarized in Table 1, have encouraged stream bank destabilization. Three lines of evidence support this conclusion: the absence of severe bank erosion and sediment wedges in presently forested basins on the Queen Charlotte Islands; the coincidence of severe bank retreat, wedge development, and logging in the study basins; and the occurrence of significant riparian erosion in other basins in the Pacific Northwest, which were subjected to similar timber harvesting practices.

Reconnaissance of other forested basins in the Queen Charlotte Islands from air photos and by FFIP personnel indicate that notable stream bank erosion and channel aggradation are not general. Because the stream banks in forested watersheds appear not to have retreated significantly despite many severe natural events that have occurred along the west coast during the 50-year period of air photo coverage, widespread stream bank destabilization must be related to special conditions in the study watersheds.

Logging activities are implicated by their temporal correspondence with stream bank retreat and sediment wedge development in the study watersheds, but the absence of wedges in other logged basins indicates that on-site circumstances are of paramount importance. The logging practices used in the study watersheds are summarized in Table 1: the common feature is the considerable extent of logging activity in the riparian zone. From investigations throughout the Pacific Northwest, it is well established that:

> "...harvesting operations that potentially cause damage to banks include felling across streams, yarding through or across streams, machine operation near streams, and the removal of vegetation which has roots that strengthen soil structure..." (Chamberlin 1982, p. 21).

All of these activities apply to the study watersheds, but Chamberlin (1982, p. 13) notes in particular that:

> "...the breakdown and destruction of stream banks by felling and yarding are among the most persistent of direct impacts of harvesting, and they are the most difficult to avoid when streamside felling or skidding and cross-stream yarding occur."

It is concluded that destabilization of the stream banks in the study watersheds was initiated by logging activities (especially felling and yarding) in the riparian zone. The erosion of the stream banks was facilitated by subsequent flood flows.

The initial erosion of destabilized stream banks shortly after logging may be accomplished by moderate stream flows. For example, Bourgeois attributed the formation of large gravel bars in the Mamin River, Queen Charlotte Islands, to erosion by moderate to high flows of 1-3 m high sand and gravel banks following timber removal from islands within the river.[1] In Armentières Creek, Mountain Creek, and Mosquito

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[1]Bourgeois, W.W. 1981. River channel and stream bank changes with logging-Mamin River. MacMillan Bloedel, Woodlands Services, Nanaimo, B.C. Unpubl. man. 10 p.

Creek tributary, bank erosion was initiated between approximately 1970 and 1974. Although the stream flows responsible are not known, the lack of severe rain storms during this period implies that exceptional hydrologic events are not a prerequisite. Large flows, however, were required to initiate the development of a sediment wedge in Lagins tributary, which was diverted along a haul road by a 1976 severe winter storm.

Field evidence suggests that high flows are a necessary but not always sufficient condition for continued bank retreat and sediment wedge growth. After the passage of a sediment "wave" through a reach, the stream channel adopts a single-thread thalweg position and alders revegetate the surface of the wedge, thereby stabilizing the remaining deposits and hindering further bank erosion. For example, the mid- and upstream portions of the sediment wedges in Armentières Creek, Mountain Creek, and Mosquito Creek tributary decreased their channel widths between 1976 and 1982 (see Table 10), despite the severe rain storm of October 31, 1978.

4 CONCLUSIONS

The objectives of this study were to identify the sources, causes, mobility, and impacts on the stream channel environment of the large, fluvial sediment accumulations present in the mid-reaches of four stream channels that have been logged to their stream banks. The following points summarize these findings:

1. Stream banks and landslides together supply two-thirds to three-quarters of all sediment delivered to the four drainage networks after logging, and the rate of delivery is substantially increased over that before logging.
2. The volume of sediment delivered to the study creeks after logging equals or exceeds the volume stored in the sediment wedges. The volumetric difference indicates a long-term sediment output rate of 600-1200 m^3/yr from Mountain Creek and Lagins Creek tributary, 200-300 m^3/yr from Armentières Creek, and negligible export from Mosquito Creek tributary, which is not greatly different than the estimated pre-logging output rates.
3. Air photo and field observations suggest that bed load is transported episodically downstream in a series of sediment "waves", so that much of the downstream wedge material is derived from the erosion and transport of upstream wedge deposits. Morphologic evidence implies intra-wedge sediment transport rates of 1600-1800 m^3/yr in Mountain Creek and Lagins Creek tributary, 500-900 m^3/yr in Armentières Creek, and 100-200 m^3/yr in Mosquito Creek tributary, 90% of it transported as bed load.
4. Stream bank destabilization appears to be caused by logging activities in the riparian zone, and especially by felling and yarding across the stream.
5. The direct effects of sediment wedge development in the channel environment include the following:
   - development of a much wider and shallower stream channel than previously existed on the site;

- deposition of channel bed gravels with texture little different than that of adjacent bank material;
- possibility for channel dewatering during low flow periods along severely aggraded reaches;
- downstream propagation of these effects over many years.

Because of the sporadic nature of bed material movement, and evidence that instream sediment transport rates have not increased greatly over pre-logging levels, it appears that the wedges may persist for decades in some reaches. Indeed, one may speculate that much of the sediment may never be removed: the stream may eventually incise a narrower channel and leave much of the "wedge" behind as a terrace, as already has occurred in reaches in Mountain Creek and Lagins Creek tributary.

6. The main recommendations to emerge from this study are that felling across streams, yarding through or across streams, and locating roads near streams must be avoided. Such recommendations have been implemented already in much of British Columbia by means of a buffer strip of timber left along the stream banks; however, the potential for blowdown is high in the Queen Charlotte Islands because of the high frequency of strong winds, and, therefore, the careful removal of timber to the streamside may be the only practical solution.

5 LITERATURE CITED

Alley, N.F. and B. Thomson. 1978. Aspects of environmental geology, parts of Graham Island. Queen Charlotte Islands. B.C. Min. Environ., Resource Analysis Branch, Bull. No. 2. 64 p.

Barr, D.J. and D.N. Swanston. 1970. Measurement of creep in a shallow, slide-prone till soil. Am. J. Sci., Vol. 269:467-480.

Beaven, L. [1986]. A synoptic survey of episodic mass movements and associated impacts on the fluvial systems of the Queen Charlotte Islands, B.C. B.C. Min. For., Land Manage. Rep. In preparation.

Bray, D.I. 1972. Generalized regime-type analysis of Alberta Rivers. Appendices A, C, D and F. Ph.D thesis. Univ. Alberta, Dep. of Civil Engineering, Edmonton, Alberta.

Chamberlin, T.W. 1982. Timber harvest. In Influence of forest and rangeland management on anadromous fish habitat in western North America. W.R. Meehan (technical editor). U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. PNW-136, 30 p.

Dietrich, W.E. and T. Dunne. 1978. Sediment budget for a small catchment in mountainous terrain. Z. Geomorph., N.F., Suppl. Bd. 29, pp. 191-206.

Dietrich, W.E., T. Dunne, N.F. Humphrey, and L.M. Reid. 1982. Construction of sediment budgets for drainage basins. In Sediment budgets and routing in forested drainage basins. F.J. Swanson, R.J. Janda, T. Dunne, and D.N. Swanston (editors). U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. PNW-141, pp. 5-23.

Fiksdal, A.J. 1974. A landslide survey of the Stequaleho Creek watershed. Fisheries Research Institute. Univ. Washington, Seattle, Suppl. to Final Report. FRI-UW-7404. 8 p.

Hack, J.T. 1957. Studies of longitudinal stream profiles in Virginia and Maryland. U.S. Geological Survey Prof. Paper. 294-B, pp. 45-94.

Hall, J.D., M.L. Murphy, and R.S. Aho. 1978. An improved design for assessing impacts of watershed practices on small streams. Verh. Internat. Verein. Limnol., Vol. 20:1359-1365.

Hartman, G.F. (editor). 1982. Proc. of the Carnation Creek workshop: 10-year review. Malaspina College, Nanaimo, B.C., Feb. 24-26, 1982. 404 p.

Hogan, D.L. 1986. Channel morphology of unlogged, logged, and debris torrented streams in the Queen Charlotte Islands. B.C. Min. of For. and Lands. Land Manage. Rep. No. 49. 94 p.

Hornbeck, J.W. and K.G. Reinhart. 1964. Water quality and soil erosion as affected by logging in steep terrain. J. Soil and Water Conserv., Vol. 19(1):23-27.

Karanka, E.J. 1986. Trends and fluctuations in precipitation and stream runoff in the Queen Charlotte Islands. B.C. Min. For., Land Manage. Rep. No. 40. 71 p.

Kelsey, H.M. 1982. Hillslope evolution and sediment movement in a forested headwater basin, Van Duzen River, North Coastal California. In Sediment budgets and routing in forested drainage basins. F.J. Swanson, R.J. Janda, T. Dunne, and D.N. Swanston (editors). U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. PNW-141, pp. 86-96.

Lehre, A.K. 1982. Sediment budget of a small Coast Range drainage basin in North-central California. In Sediment budgets and routing in forested drainage basins. F.J. Swanson, R.J. Janda, T. Dunne, and D.N. Swanston (editors). U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. PNW-141, pp. 67-77.

Lyons, J.K. and R.L. Beschta. 1983. Land use, floods, and channel changes: Upper Middle Fork Willamette River, Oregon (1936-1980). Water Resources Res. 19:463-471.

Mackin, J.H. 1948. Concept of the graded river. Geol. Soc. Am. Bull, Vol. 59:463-512.

Madej, M.A. 1982. Sediment transport and channel changes in an aggrading stream in the Puget Lowland, Washington. In Sediment budgets and routing in forested drainage basins. F.J. Swanson, R.J. Janda, T. Dunne, and D.N. Swanston (editors). U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. PNW-141, pp. 97-108.

Megahan, W.F. and W.J. Kidd. 1972a. Effect of logging roads on sediment production rates in the Idaho Batholith. U.S. Dep. Agric. For. Serv. Res. Pap. INT-123. 14 p.

_____. 1972b. Effects of logging and logging roads on erosion and sediment deposition from steep terain. J. For., Vol. 70 (3):136-141.

Miller, J.P. 1958. High mountain streams: effects of geology on channel characteristics and bed material. New Mexico State Bureau of Mines and Mineral Resources. Memoir 4. 53 p.

Milne, W.G., G.C. Rogers, R.P. Riddihough, G.A. McMechan, and R.D. Hyndman. 1978. Seismicity of western Canada. Can. J. Earth Sci., Vol. 15:1170-1193.

Morrison, P.H. 1975. Ecological and geomorphological consequences of mass movements in the Alder Creek watershed and implications for forest land management. B.A. thesis. Univ. Oregon, Eugene, Oreg. 102 p.

O'Loughlin, C.L. 1972. An investigation of the stability of steepland forest soils in the Coast Mountains of Southwest British Columbia. Ph.D. thesis. Univ. B.C., Vancouver, B.C. 147 p.

Pearse, P.H. 1982. Turning the tide: a new policy for Canada's Pacific fisheries. The Commission on Pacific Fisheries Policy, Final Report, Vancouver, B.C. 292 p.

Poulin, V.A. 1984. A research approach to solving fish/forestry interactions in relation to mass wasting on the Queen Charlotte Islands. B.C. Min. For., Land Manage. Rep. No. 27. 16 p.

Reid, L.M. 1981. Sediment production from gravel-surfaced forest roads, Clearwater Basin, Washington. Univ. Washington, College of Fisheries, Fisheries Research Inst., FRI-UW-8108. 247 p.

Reid, L.M. and T. Dunne. 1984. Sediment production from forest road surfaces. Water Resources Res. 20:1753-1761.

Reid, L.M., T. Dunne, and C.J. Cederholm. 1981. Application of sediment budget studies to the evaluation of logging road impact. N.Z. J. Hydrol. 20(1):49-62.

Rice, R.M. 1981. A perspective on the cumulative effects of logging on streamflow and sedimentation. In Cumulative effects of forest management on California watersheds: an assessment of status and need for information. Proc. of the Edgebrook Conf., Berkeley, California, June 2-3, 1980. R.B. Standiford and S.I. Ramacher (editors), pp. 36-46.

Richards, K. 1982. Rivers: form and process in alluvial channels. Methuen, London, England. 358 p.

Roberts, R.G. 1984. Stream channel stability in the Queen Charlotte Islands: an examination of Schumm's fluvial model. M.Sc. thesis. Univ. B.C., Vancouver, B.C. 198 p.

Rood, K.M. 1984. An aerial photograph inventory of frequency and yield of mass wasting on the Queen Charlotte Islands, British Columbia. B.C. Min. For., Land Manage. Rep. No. 34. 55 p.

Salo, E.O. and C.J. Cederholm. 1981. Cumulative effects of forest management on watersheds - some aquatic considerations. In Cumulative effects of forest management on California watersheds: an assessment of status and need for information. Proc. of the Edgebrook Conf., Berkeley, California, June 2-3, 1980. R.B. Standiford and S.I. Ramacher (editors), pp. 67-78.

Smith, R.B. 1982. Effects of mass wasting on vegetation succession, soil development and forest growth on the Queen Charlotte Islands. FFIP Working Pap. 8/83. 8 p.

Strahler, A.N. 1952. Hypsometric (area-altitude) analysis of erosional topography. Geol. Soc. Am. Bull., Vol. 63:1117-1142.

Sutherland Brown, A. 1968. Geology of the Queen Charlotte Islands, British Columbia. B.C. Dep. of Mines Pet. Resources. Bull. No. 54. 226 p.

Swanson, F.J. and C.T. Dyrness. 1975. Impact of clear-cutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon. Geology 3:393-396.

Swanson, F.J. and R.L. Fredriksen. 1982. Sediment routing and budgets: Implications for judging impacts of forestry practices. In Sediment budgets and routing in forested drainage basins. F.J. Swanson, R.J. Janda, T. Dunne, and D.N. Swanston (editors). U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. PNW-141, pp. 129-137.

Swanson, F.J., R.L. Fredriksen, and F.M. McCorison. 1982a. Material transfer in a western Oregon forested watershed. In Analysis of coniferous forest ecosystems in the western United States. R.L. Edmonds (editor). Hutchinson Ross, Stroudsburg, Penn., pp. 233-266.

Swanson, F.J., R.J. Janda, T. Dunne, and D.N. Swanston (editors). 1982b. Sediment budgets and routing in forested drainage basins. U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. PNW-141, 165 p.

Swanson, F.J., M.M. Swanson, and C. Woods. 1981. Analysis of debris-avalanche erosion in steep forest lands: an example from Mapleton, Oregon, USA. In Erosion and sediment transport in Pacific Rim steeplands. IAHS Publ. No. 132. T.R.H. Davies and A.J. Pearce (editors), pp. 67-75.

Swanston, D.N. 1981. Creep and earthflow erosion from undisturbed and management impacted slopes in the Coast and Cascade Ranges of the Pacific Northwest, U.S.A. In Erosion and sediment transport in Pacific Rim steeplands. IAHS Publ. No. 132. T.R.H. Davies and A.J. Pearce (editors), pp. 76-94.

Toews, D.A.A. and M.K. Moore. 1982. The effects of three streamside logging treatments on organic debris and channel morphology of Carnation Creek. In Proc. of the Carnation Creek workshop: a 10-year review. Malaspina College, Nanaimo, B.C., Feb. 24-26, 1982. G.F. Hartman (editor), pp. 129-153.

Valentine K.W.G., P.N. Sprout, T.E. Baker, and L.M. Lavkulich. 1978. The soil landscapes of British Columbia. B.C. Min. Environ., Resource Analysis Branch. 197 p.

Wilford, D.J. and J.W. Schwab. 1982. Soil mass movements in the Rennell Sound Area, Queen Charlotte Islands, British Columbia. Proc. Canadian Hydrology Symp. '82: Hydrological Processes of Forested Areas, June 14-15, 1982, Fredericton, N.B., Assoc. Committee on Hydrol., N.R.C.C., pp. 521-541.

Wolman, M.G. 1954. A method of sampling coarse river-bed material. Am. Geophys. Union, Trans. 35, pp. 951-956.